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# JOURNAL OF THE AERONAUTICAL SCIENCES


VOL. 3 FEBRUARY, 1936 NO. 4

*Editor:* J. C. HUNSAKER, *Massachusetts Institute of Technology*

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# *An Appreciation*

The publication of the Journal of Aeronautical Sciences is made possible by contributions made by manufacturers or operators of aircraft and producers of equipment or supplies used in aeronautics. The Institute appreciates the cooperation of the companies listed below.

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# JOURNAL OF THE AERONAUTICAL SCIENCES

Volume 3 FEBRUARY, 1936 Number 4


## Fourth Annual Meeting of the Institute of the Aeronautical Sciences

THE Fourth Annual Meeting of the Institute of the Aeronautical Sciences, Inc., was held in the Pupin Physics Laboratories of Columbia University, New York City, on January 29, 1936. Charles L. Lawrance, Chairman of the Council, presided in the absence of Donald W. Douglas. Lester D. Gardner acted as Secretary.

After the minutes of the previous meeting had been read and approved, the President's Annual Report was read.

### The President's Annual Report

ON September 30, 1935, the Institute completed its third fiscal year. This report covers not only that period but up to January 1, 1936.

The progress made by the Institute during its third year has been notable. Growth in membership, financial stability, increase in activities, and prestige, are evidences of the soundness of the plans of the Founders. Even more significant is the fact that the Institute is coming to be regarded as a worthy recipient of legacies made for the advancement of aeronautics.

The Treasurer's report will give the financial condition of the Institute. From this it will be observed that while the Institute is conservatively managed, and operates within its budget, the funds available are small in amount when compared with those of other scientific and engineering societies. As similar service is expected one of the problems which should be given consideration is how the revenue of the Institute may be increased so that an adequate staff may be available to enable the Institute to function as it should; the Journal to be edited by other than voluntary assistance and the Secretary to be relieved of much of the detail work he has done for the past three years. A plan has been proposed by the Council for a new grade of Corporate Membership. If the various organizations which are receiving benefits from the work of aeronautical engineering and scientific specialists will contribute to the budget of the Institute, many activities which are now impossible to undertake will be available to members.

*Reed Bequest.* While the present Treasurer's Report does not include the gift, as it was received after the close of the fiscal year, the outstanding financial gain of the year was the receipt of the bequest from the estate of the late Dr. S. A. Reed of Ten Thousand Dollars to endow the "Sylvanus Albert Reed Award." The generosity of Dr. Reed, who was not only a Fellow but also the first Honorary Member of the Institute, was recognized with great appreciation when he created the Award. When he died, the Council expressed the sorrow of the Institute by a formal resolution. Again, at this Annual Meeting, your President expresses the regret of the membership in the loss of so eminent a member.

*Prospective Legacies.* One of the objects of Dr. Reed in making the Institute the custodian of this bequest was his belief that it would stimulate others to make similar bequests. A friend of the Institute, when he learned of Dr. Reed's generosity, placed in his will a bequest to the Institute and executed a Deed of Gift which outlines the purposes for which he, at present, wishes the fund to be used. Originally the donor intended to leave Five Hundred Thousand Dollars outright for the Fund, but, as among his investments he has large interests in aeronautical activities, he decided to leave instead securities which he believed could be liquidated better by a committee of Institute members than by his executors.

In making this bequest and permitting the announcement of it at this time, the donor, following the precedent of Dr. Reed, hopes that it may cause others to regard the Institute worthy of gifts, bequests and support.

While the name of the donor must obviously be withheld, your President wishes the members to know that such a bequest is in existence. It is to be hoped that this evidence of confidence in the Institute may bring the results hoped for by the donor but that it may be many, many years before it comes to the Institute. It is not inappropriate for your President to mention that a bequest of such a size imposes an obligation on members to maintain the prestige and activities of the Institute so that the donor will not in the future feel that the Institute is no longer worthy to become the custodian of such a substantial fund.

*The Journal.* The Journal was changed from a quarterly to a bi-monthly in 1935. This year the Council determined to issue the Journal monthly so that the many papers which are available may be published promptly. This country will now have a scientific and engineering publication published as frequently as many similar publications in Europe. The publication of the Journal has been possible only by the editorial service rendered by Dr. Hunsaker. I am sure that I record the appreciation of every member when I again express the great obligation felt by the Council and members to Dr. Hunsaker for his untiring efforts to make the Journal reflect the progress being made in this country in the aeronautical sciences. As the Journal becomes better known in all parts of the world, the aeronautical scientific work done in the United States will be judged by the high standard of papers it publishes. It is therefore to the advantage of every member to submit to the Editorial Board for their consideration the results of his latest work.

*The Aeronautical Index.* The Institute has been fortunate in receiving a grant from the Works Progress Administration for the compilation of an index of aeronautics which already is the most comprehensive in existence. Over forty thousand dollars will have been spent for salaries of unemployed workers before the project is terminated. The Institute appreciates the cooperation that it has received from the administrators of the Works Progress Administration and will endeavor to make this index a permanent contribution to the knowledge of aeronautics. To Sherman M. Fairchild and Luis de Florez the Institute is indebted for furnishing the funds for equipment and additions which could not be supplied by the government.

*Administration.* The work of the Institute has been hampered by its being unable to employ a staff to handle adequately its expanding activities. The Secretary and two assistants have not only carried forward the work of the Institute and the publication of the Journal but supervised the preparation of the Index. Through the courtesy of the airlines, the Secretary has flown over twenty thousand miles during the last year attending meetings of sections and conducting the affairs of the Institute.

*Scientific and Engineering Members.* When the Institute was organized, certain members were designated as "Scientific Members." Later a grade of "Engineering Members" was created. Having the two grades led to certain difficulties owing to the overlapping of fields of activity of persons engaged in aeronautical scientific as well as engineering work. Following the recent trend in all technical societies to simplify the grading of members and to increase further the prestige of election to membership in the Institute, the members at this Annual Meeting will vote on the combination of these two grades into one under the name of "Members."

*Fellows.* The wise restriction of the founders of the Institute to limit the election of Fellows to ten annually has been fully justified by the high standing of the Fellows elected last year. There are many members whose work entitles them to the grade of Fellow and who eventually will be advanced to this grade, but the procedure of election to this grade by a ballot on many names increases the distinction of membership in this group and prevents undue haste in the selection of additional Fellows.

*Honorary Fellows.* Similarly, the election of only one Honorary Fellow each year by the Fellows has made the distinction of this grade of membership outstanding. Dr. von Karman was added to the distinguished list this year and all members will join with me, I feel sure, in regarding this honor as not only deserved but as also reflecting distinction on the Institute.

*Membership.* As will be seen from the Secretary's report the growth of membership of the Institute during the last year shows substantial gains. This has been due largely to the creation of the grade of Student Members and making the dues for this grade nominal. It was the feeling of the Council that students should be accepted for membership and permitted to share in the advantages of participation in the activities of the Institute during the period of preparation for their professional careers. It was also agreed that any expense of maintaining this grade of membership should be borne by the Institute out of its general funds as a contribution to aeronautical education.

I cannot close without paying tribute for the untiring zeal and cooperation of Major Gardner, Secretary of the Institute. He has kept close contact with our members to observe their needs first hand and reported them to the Council and Officers for appropriate actions. Without him we could not have made the real progress we have; he has contributed so much that I cannot enumerate it in this report.

In closing this Annual Report I wish to thank the other officers, the Council and the Advisory Board, and the members of various committees for the able and untiring efforts they have given to the work of the Institute. One of the results of having your President located at a considerable distance from the headquarters of the Institute has been a demonstration that the Institute is now organized so that it can function with only general guidance from the Officers and Council.

The Institute has had a remarkable growth in the last three years. Its future is assured if every member will feel that organizations become strong only through the cooperation of members.

DONALD W. DOUGLAS

Major E. E. Aldrin, Treasurer of the Institute, presented the Treasurer's Report for the fiscal year ending September 30, 1935.

## THE TREASURER'S REPORT

The Treasurer submits herewith the Annual Financial Statement of the Institute for the fiscal year which ended September 30, 1935, as required by the By-Laws.

With the approval of the Council, I arranged to have the Comptroller's Department of the Standard Oil Company of New Jersey audit the books of the Institute. I have submitted the letter of transmittal to the Council which states that "matters were found in a satisfactory condition."

The most important item in any financial statement during these times is the one which shows either red or black. While small, the item of $462.48 is black and indicates that the Institute lives within its means.

One important addition to the assets of the Institute cannot be included in the statement. The cost of the Aeronautical Index has already been about $20,000. As this has been contributed and paid for by the Government, it is not proper to set it up in our accounts.

The net unexpended incomes or surplus stands at $6,338.22. Since September 30, 1935, this item has been increased by $10,000, the legacy from the estate of Dr. S. A. Reed.

It will be noted that a reasonable relationship is maintained between accounts payable and accounts receivable.

The increase in dues is reflected in the increase of income from this source from $1,705.51 to $4,854.47. This is the net amount after $2.00 has been deducted from each member's payment for a subscription to the Journal, as required by the postal regulations.

Members will observe that of the total income of the Institute, approximately one-fourth is from dues. The aircraft industry contributed $4,944.50 in the form of advertising. Revenue from subscriptions to the Journal also helped.

### Annual Balance Sheet
### As of September 30, 1935

| | | |
|---|---|---|
| *Assets* | | |
| Cash in Bank and on Hand | | $868.67 |
| Accounts Receivable | | 2,269.70 |
| Office Furniture and Equipment | $4,451.55 | |
| *Less* | | |
| Reserve for Depreciation | 1,251.70 | |
| | | 3,199.85 |
| | | $6,338.22 |
| *Liabilities and Capital* | | |
| Accounts Payable | | $1,705.10 |
| *Net Unexpended Income* | | |
| Balance September 30, 1934 | $4,170.64 | |
| Net Unexpended Income for year ended September 30, 1935 | 462.48 | |
| | | 4,633.12 |
| | | $6,338.22 |

*Operating Statement for the Year Ended September 30, 1935*

| | | |
|---|---|---|
| *Income* | | |
| Dues | | $4,854.47 |
| Initiation Fees | | 512.00 |
| Donors | | 2,349.45 |
| *Journal* Advertising | $4,944.50 | |
| *Journal* Subscriptions (Members and Others) | 3,129.14 | |
| | | 8,073.64 |
| Certificate of Membership Receipts | | 38.00 |
| Accounts Receivable: | | |
| Dues — 1934 | $30.00 | |
| Dues — 1935 | 305.00 | |
| Donors | 400.00 | |
| *Journal* Advertising | 1,371.42 | |
| *Journal* Subscriptions | 120.98 | |
| | | 2,227.40 |
| Miscellaneous Sales | | 261.18 |
| | | $18,316.14 |
| *Expenses* | | |
| Agents' Commissions | $411.26 | |
| Collection and Exchange | 3.13 | |
| Discount | 32.61 | |
| Electricity | 57.70 | |
| Meetings | 35.63 | |
| Miscellaneous | 392.28 | |
| Office Supplies | 183.13 | |
| Postage | 545.65 | |
| Printing and Stationery | 713.03 | |
| Rent | 1,000.00 | |
| Telephone and Telegraph | 395.74 | |
| Travel | 239.25 | |
| *Journal* Printing, Promotion, and Salaries | 8,248.54 | |
| Administrative, Clerical, and Accounting | 4,954.50 | |
| Depreciation | 556.31 | |
| Uncollectable Dues | $75.00 | |
| Uncollectable Subscriptions | 9.90 | |
| | 84.90 | |
| | | 17,853.66 |
| *Net Unexpended Income* | | $462.48 |

The members should also know that E. L. Cord and Donald W. Douglas became Benefactor Members in 1935 by contributing $1,000 each. It was these gifts that enabled the Institute to maintain its activities to an extent comparable to the previous year when donors contributed over $7,000.

As will be seen, the expense of the Journal has been the largest expense of the Institute. As many of the other items are also publication expense, it may be said that about two-thirds of the expenses of the Institute have some relation to the Journal.

One remarkable item is the $35.63 for Meetings' Expense. This shows that our Secretary and the Pacific Coast Section have managed in some way to make the meetings and dinners support themselves. Later, when the Institute has a larger income, more money should be available for this important activity of the Institute.

The salary item speaks for itself. The Institute has had to function without stenographers, clerks, or bookkeeper, all the work being done by the Secretary and two capable assistants. They not only keep all the records of the Institute, answer the innumerable calls for information, handle all the details of publishing a magazine, but try to keep up to date the ever increasing correspondence.

Having had two years experience as Treasurer of a new society, I can speak feelingly when I urge the aircraft industry to assist the Institute by contributing to its upkeep so that it may have adequate personnel to operate without requiring night and day work of an overburdened staff.

The Secretary has managed to keep the Institute on a sound financial basis by efforts which he will not permit me to relate. If the Institute with its limited resources has been able to receive one legacy of $10,000, over $40,000 for the Aeronautical Index, and arouse the interest of a friend to such an extent that he is willing to make it the custodian of $500,000, what might be accomplished if it is able to carry out many activities not now possible?

Major Lester D. Gardner read the Report of the Secretary.

### The Secretary's Annual Report

*Membership.* The Membership Report as of January 1, 1936, is as follows:

| | |
|---|---|
| Membership on January 1, 1935 | 905 |
| Members elected during 1935 | 440 |
| Resigned | 6 |
| Deceased | 6 |
| Dropped | 28 |
| Total Membership on January 1, 1936 | 1,305 |

The division of the membership by classes is as follows:

| | *Foreign* | *American* | *Total* |
|---|---|---|---|
| *Honorary Fellows* | 1 | 4 | 5 |
| *Fellows* | 0 | 47 | 47 |
| *Scientific Members* | 94 | 118 | 212 |
| *Engineering Members* | 77 | 303 | 380 |
| *Technical Members* | 0 | 132 | 132 |
| *Pilot Members* | 5 | 70 | 75 |
| *Industrial Members* | 8 | 148 | 156 |
| *Student Members* | 0 | 298 | 298 |
| Total | 185 | 1,120 | 1,305 |

As no special effort has been made to secure new members, the growth in membership indicates that the Institute is now regarded as part of an aeronautical specialist's professional equipment.

The large number of Student Members presents a problem which the Council hopes may be solved by a Committee on Student Affairs which has been appointed. The interest shown by the Student Branches that have been formed gives promise of a source of new members for the Institute each year as classes are graduated.

*The Journal.* The publication of the Journal as a monthly will place a burden on the staff of the Institute unless a substantial income is received from the new grade of Corporate Members. Last year, members were urged to bring the Journal to the attention of those persons in their organizations who could aid in securing advertising support for the Journal. This

has been done with good results by some members but, with the change from six to twelve issues a year, it will become more necessary than before.

*The Skyport.* The Institute has been fortunate in being able to remain at Rockefeller Center at a rent it has been able to pay. When the Skyport was first provided, it appeared to be too large for the limited activities of the Institute. With the demands for service increasing each month, the question of space will become acute this year.

There has been a tendency on the part of members to send applicants for employment, persons with aeronautical inventions and problems, and letters of enquiry to the Secretary with an intimation that he can help them. The procession of these persons takes much of the time of the Secretary and as he is not usually able to do more than be courteous to those referred to him, they go away disappointed. Will members please show consideration and send to the Institute only persons whose need can be properly handled by a scientific society?

*Library.* Our library continues to grow slowly, largely through books sent for review. The acquisition of a large collection of books so that the Institute may have a library of the leading aeronautical works is a matter which should receive consideration.

*Awards.* The death of Dr. S. A. Reed has deprived the Institute of a valued counselor. His interest in all the affairs of the Institute was so sincere and his advice so helpful that he will be greatly missed by those who are guiding the affairs of the Institute. As the legacy which he left to the Institute has been paid, an obligation is created to make the Award which he endowed pre-eminent in the field of the aeronautical sciences. The membership should know and appreciate the fact that the money for this year's Award was generously provided by Dr. Reed's heirs. Other awards are under consideration and it is hoped that during the coming year they may become available.

*Bequests.* An indication of the Institute's future possibilities is evident from the bequest which has been made in the will of a friend. Many members have regarded the Institute as just another society. Those who made the original plans for the Institute and carried them forward to their present state believed that they were creating an organization which would be worthy of endowments. That they were correct in their belief has been demonstrated to a degree that they never could have foreseen. The bequest referred to is only one of several that may be in existence, unbeknown to anyone. It is seldom that such matters may be referred to. With these possibilities in view, members are urged, in discussing affairs of the Institute, to keep in mind that what they say may have a more important result than they know.

*Index.* The Aeronautical Index which is being prepared with the aid of unemployed workers supplied by the Works Progress Administration is nearing completion. By July, it is hoped, it will contain as many references to all subjects related to aeronautics as will be required by any person desiring to be put in touch with the principal work done in a specialized field.

Over 200,000 cards containing over a half a million references have been filed and are being classified. Six or seven workers are engaged in translating the titles and digests of articles in French, German, Italian, as well as other languages so that those who are not able to translate for themselves may be able to learn what has been published abroad in many fields.

The W. P. A. is spending about $40,000 in salaries for this project and when it is completed the Institute will have available for aeronautical research workers the only such index in existence. Your Secretary knows from the comment of the many members who have used the files in their present unfinished condition that the Index will make the Institute a center for aeronautical information unequalled in this country. Bibliographies on special subjects are being prepared which will be available to members who cannot consult the file personally. Later, when the files are completed, it is believed that it will be possible to keep them up to date and furnish a service by mail to all members.

The supervision of the project has placed an added burden on the staff of the Institute, but as it will not continue indefinitely and as it had to be done now or never, the extra responsibilities were cheerfully undertaken. Not only should members appreciate the fine cooperation received from the W. P. A. but from many organizations in this country and abroad. Particular mention should be made of the National Advisory Committee for Aeronautics and the Library of Congress for their assistance.

To the officers and committees who have done splendid work during the past year your Secretary expresses his appreciation. All have given of their time and ability when needed. Otherwise, with a staff of three the Institute could not have carried on. Donald W. Douglas, while living at a distance from headquarters, has given much time to the affairs of the Institute and Major Aldrin, our Treasurer, has kept the finances of the Institute in good condition for the past two years.

The members of the Admissions Committee have spent many hours in examining the qualifications of four hundred applicants for membership. Their work does not show in the reports, but the membership roster and the high membership standards maintained in the various grades indicate the conscientious work that the members of this committee have done.

Once more your Secretary asks that any shortcomings on his part be condoned. He has tried to look after the more important matters and neglected doing only those things which could be postponed without endangering the progress of the Institute. With plans which the Council has for increasing the staff of the Institute during the coming year, there is no doubt that members will find that a more complete and satisfactory service will be rendered next year and that the Institute will become what it should be—a society which keeps its members informed of current work being done in the aeronautical sciences, a place where information regarding any phase of aeronautics may be found and, what is equally necessary, a headquarters where members can come and receive a cordial greeting. With continued cooperation of members, your Secretary believes that the future holds unlimited possibilities for the Institute. Vision combined with sound ideas will always achieve its ends.

LESTER D. GARDNER

The minutes of the last Annual Meeting held on January 30, 1935, were read and were approved.

The presiding officer appointed Messrs. A. P. Loening, James B. Taylor, and E. Burke Wilford to act as tellers of the proxies and requested them to report as soon as they had counted the proxies. Mr. A. P. Loening reported for the tellers that they had examined the proxies and found 222 had been received in good order. He reported that 176 had voted favorably on the proposed change in the Constitution, 14 were opposed, and 32 had not voted.

The Secretary reported that he had complied with the Constitution and By-Laws in sending out the required notices and proposed the following amendment to the Constitution of the Institute of the Aeronautical Sciences, Inc.:

That Section 1, Article II of the Constitution of the Institute of the Aeronautical Sciences, Inc., be amended by omitting therefrom the words "Scientific Members" and "Engineering Members" and substituting therefor the word "Members."

The amendment to the Constitution was unanimously adopted as read.

Dr. G. W. Lewis, Chairman of the Nominating Committee, placed in nomination the following members to serve for a term of three years each on the Council: Charles L. Lawrance, Paul Kollsman, Earl D. Osborn and T. P. Wright.

He also nominated the following members to serve for one year on the Advisory Board: Edmund T. Allen, Lyman J. Briggs, James H. Doolittle, Vincent Bendix, V. E. Clark, Jack Frye, W. R. Gregg, Hall L. Hibbard, E. J. King, I. Machlin Laddon, John K. Northrop, A. E. Raymond, James M. Shoemaker, Gerard F. Vultee, Leroy R. Grumman, J. H. Kindelberger, Alexander Klemin, Grover Loening, A. A. Priester, H. J. E. Reid, E. A. Stalker and O. Westover.

The meeting voted to elect to the Council and Advisory Board the names presented by the Nominating Committee.

The presiding officer called for nominations for the Nominating Committee for the ensuing year. The following members were nominated and elected.

G. W. Lewis, Chairman; Alexander Klemin, Glenn L. Martin, Holden C. Richardson, Ralph H. Upson.

The presiding officer declared a recess of five minutes so that the Council could formally elect officers for the ensuing year. On reconvening, the Secretary announced the election of the following officers to serve for one year.

President, Glenn L. Martin; Vice-Presidents, E. E. Aldrin, C. L. Egtvedt, Clark B. Millikan, G. W. Lewis, Eugene E. Wilson; Treasurer, Sherman M. Fairchild.

The members expressed their appreciation of the work of the officers for the past year.

Mr. Lawrance called the newly elected President of the Institute, Mr. Glenn L. Martin, to the Chair. Mr. Martin expressed his appreciation of the honor of his election and assured the members of his desire to do all he could to make the next year one of progress for the Institute.

The President announced the election of Dr. Wm. F. Durand as Honorary Fellow for 1935 *"For his contributions to hydrodynamics, thermodynamics, and aerodynamics, particularly with relation to the advancement of the knowledge of air propellers. For his supervision of a review of the development of aerodynamic theory since flight in heavier-than-air craft became an assured fact."*

The President announced the election of Dr. Th. von Karman as Honorary Fellow for 1936 *"For notable contributions to theoretical aerodynamics."*

The President paid a tribute to the memory of Dr. S. A. Reed, Honorary Member and Fellow of the Institute, who died on October 1, 1935. He expressed for the members the greatest appreciation of the Institute for the bequest of $10,000 which Dr. Reed left to endow the "Sylvanus Albert Reed Award." He said that the distinguished career of Dr. Reed as well as his fine character imposed an obligation on the Fellows of the Institute to make the Award the most distinguished honor in the field of the aeronautical sciences. The President also expressed the appreciation of the Institute to the heirs of Dr. Reed for a gift of $250 to be presented with the certificate this year.

The President announced that the Reed Award for 1935 had been made to Frank W. Caldwell *"For increasing the effectiveness of aircraft through development and improvement of controllable and constant speed propellers."*

The President expressed the appreciation of the Institute to Columbia University and especially to Prof. George B. Pegram for the use of the Pupin Physics Laboratories building and the Faculty Club for the Annual Meeting and Annual Dinner. It was voted to express the appreciation of the Institute to Columbia University and Professor Pegram. President Martin again expressed to the outgoing officers the appreciation of the membership for their work. The meeting then adjourned.

## Fourth Annual Dinner

The Annual Dinner of the Institute of the Aeronautical Sciences was held at the Faculty Club of Columbia University on Thursday, January 30th. Over three hundred members and guests attended.

Charles L. Lawrance, past president of the Institute, introduced Glenn L. Martin, President for 1936. Mr. Martin complimented the officers and the Council on the progress made by the Institute during the past year and expressed the hope that the officers for the coming year would receive the support and encouragement from the members that they had given the officers and Council during the past three years. He said that he would do all he could to advance the interests of the Institute so that it could render a greater service to members. The fact that an anonymous donor had been so impressed with the confidence of Dr. S. A. Reed in making the Institute custodian of a bequest for an award that he had decided to bequeath to the Institute securities valued at five hundred thousand dollars indicated, Mr. Martin said, that the Institute had accom-

Mr. Glenn L. Martin (left), newly elected President, presenting certificate of "Sylvanus Albert Reed Award" to Mr. Frank W. Caldwell.

plished more than even the members believed would be possible in three years. He thanked the donor on behalf of the members and said that he hoped that other friends would be influenced by his generosity to make further gifts or bequests. The President then called on Major Lester D. Gardner to pay a tribute to Dr. S. A. Reed and tell of the origin of the "Sylvanus Albert Reed Award."

Major Gardner expressed the regret he knew all members felt over the loss of one of the most distinguished members and best friends of the Institute. He told how he had spoken to Dr. Reed about an award for achievements in the aeronautical sciences, and how Dr. Reed had immediately agreed to establish and endow such an award. The specifications, Major Gardner said, were carefully prepared by Dr. Reed, who wanted the recipient to be a person who had made a valuable contribution to the advancement of the aeronautical sciences and who had developed his work to a state where it was rendering a practical service to aviation. When Dr. Reed died in October, his heirs paid to the Institute the ten thousand dollars bequest within sixty days and the money had been invested, as required by the will, in government bonds. The heirs, wishing to have the award made for 1935, contributed $250 additional. Major Gardner expressed the appreciation of members for their generosity.

Major Gardner said that he believed that, with the confidence shown by two friends in the Institute, other gifts were either being considered or possibly had been made, unknown to anyone.

Dr. J. C. Hunsaker was requested by President Martin to give an account of the achievements of Mr. Frank W. Caldwell, recipient of the Reed Award for 1935. He related the following:

Frank Walker Caldwell was born on December 20, 1889, at Lookout Mountain, Tennessee. He attended public school through high school when he entered the Tome Preparatory School for Boys at Port Deposit, Maryland. He then spent one year at the University of Virginia and in 1908 entered Massachusetts Institute of Technology where he took a Mechanical Engineering Course. At this time the college curriculum did not offer a course in aeronautics but Mr. Caldwell was highly interested in aeronautical developments. It was while attending M.I.T. that he and a fellow student built a glider which they entered in a contest. This contest the boys won. While at M.I.T. Mr. Caldwell wrote a thesis on propellers, which was his chief interest. He graduated from Massachusetts Institute of Technology in 1912. After graduating from M.I.T., he became associated with the firm of Stone and Webster in Iowa but did not remain there long as the business took him away from his chief interest—aeronautics.

Mr. Caldwell was made chief of the propeller department of the Curtiss Aeroplane & Motor Company at Buffalo, New York, early in 1916. While there, the United States Government had a disagreement with the Republic of Mexico which caused many troops to be concentrated along the Mexican border. Along with the troops went airplanes. The propellers on the planes would not stay together. General Pershing who was then in command sent the Curtiss plant a wire telling them of the existing conditions in the Flying Corps. Mr. Caldwell, with a corps of men, was dispatched to the Border to remedy the trouble. After experimenting with the propellers for some time it was found that the propellers glued in New York State would not stand the intense heat of the Border, so Caldwell developed a special procedure for treating the wood.

It was not long after finishing the job on the Border that Mr. Caldwell was called to Washington and given the position of Chief of the Propeller Engineering Division of the Army Air Service which position he held until resigning in August, 1928. At the Army Experimental Station Mr. Caldwell did extensive work in designing machinery for testing propellers. He also developed many new improvements in the design of wood, micarta, and metal propellers. From August, 1928, until about the first of June, 1929, Mr. Caldwell maintained an office in Dayton, Ohio, in the capacity of Aeronautical Engineer.

On June 1, 1929, Mr. Caldwell entered the employ of the Standard Steel Propeller Company as Chief Engineer and at the present time is Engineering Manager of Hamilton Standard Propellers Division, United Aircraft Manufacturing Corporation. Mr. Caldwell graduated with a B.S. degree from M.I.T. and is a member of the Tome Cum Laude Society as a result of very high scholarship. He is a member of the Society of Automotive Engineers and a Fellow of the Institute of the Aeronautical Sciences. The Hamilton Standard Propeller Company was awarded the Collier Trophy for 1933 for the controllable pitch propeller designed by Mr. Caldwell for this company.

Mr. Martin, in presenting the Certificate and check for $250, told Mr. Caldwell that the Award was not made by a small committee, but after a series of secret ballots by the forty-seven Fellows of the Institute. He said that the Award was not only a distinguished honor, but represented the opinion of Mr. Caldwell's fellow workers in the field of aeronautics. He then read the Award which was as follows:

"The Sylvanus Albert Reed Award for a notable contribution to the aeronautical sciences resulting from experimental or theoretical investigations, the beneficial influence of which on the development of practical aeronautics is apparent. The Fellows of the Institute of the Aeronautical Sciences have selected Frank Walker Caldwell to receive the award for the year 1935, *For increasing the effectiveness of aircraft through development and improvement of controllable and constant speed propellers.*"

In accepting the Award, Mr. Caldwell said that he appreciated receiving the certificate bearing the name and picture of Dr. Reed who pioneered in the field of metal propellers. He hoped that it would be an incentive to him to aid in making further progress in advancing the speed and performance of aircraft.

Dr. George W. Lewis gave a history of the work of Dr. Wm. F. Durand in the field of the aeronautical sciences and Mr. Martin conferred on him the Honorary Fellowship of the Institute for 1935 *"For his contributions to hydrodynamics, thermodynamics, and aerodynamics, particularly with relation to the advancement of the knowledge of air propellers. For his supervision of a review of the development of aerodynamic theory since flight in heavier-than-air craft became an assured fact."*

In acknowledging the honor Dr. Durand complimented the Institute on its rapid growth and the sound principles on which it was founded.

Mr. Martin, in conferring on Major General Benjamin D. Foulois the Honorary Membership of the Institute, told of the early days in aviation when General Foulois was the sole pilot in the Army and had the first military aeroplane used in this country. He read the following citation:

*"For his courageous foresight in laying the foundation of military aviation; in recognition of great personal sacrifices made in pioneering a field which has become a major factor in the national defense of all countries; for his advocacy of the premier position aircraft should occupy in commerce and military strategy; for his leadership in utilizing the aeronautical sciences for the technical development of the flying equipment of the Army."*

General Foulois, in accepting the Honorary Membership, urged the members of the Institute to keep always in mind the practical side of their work and not to devote too much of their time to the theoretical computations that had no practical utility.

Dr. J. C. Hunsaker was then asked to present to Major Gardner, Secretary of the Institute, the Diploma of Honor of the Ligue Internationale des Aviateurs *"For his great contribution to aviation."* The diploma was signed by Clifford B. Harmon, Founder of the Ligue, Colonel Charles A. Lindbergh, Eddie Rickenbacker, Lt. Colonel Harold E. Hartney, George Haldeman, Clayton Knight, Shirley Short, and Commander John W. Iseman.

Dr. Th. von Karman, Honorary Fellow for 1936.

Major Gardner thanked the gentlemen who had signed the diploma for the Ligue and related how in the early days of flying Mr. Harmon had made a world's record for overwater flying by a flight from Long Island to Greenwich, Connecticut.

Rear Admiral E. J. King, Chief of the Bureau of Aeronautics, Navy Department, Mr. Eugene L. Vidal, Director of Air Commerce, and Mr. Willis R. Gregg, Chief of the Weather Bureau, made short addresses after which D. M. Little of the U. S. Weather Bureau showed a moving picture "Clouds in Motion." Mr. Little photographed many varieties of clouds, taking pictures at the rate of one frame every three or four seconds. When projected at the regular rate, the action was speeded up approximately sixty times, and showed in a few minutes the formation and disintegration of cloud forms. Aside from the scientific interest of the film, the effects of the motion of the clouds made beautiful and startling pictures.

Eastman N. Jacobs then gave a resumé of a paper which he had presented in October at the Volta Congress in Rome on "Methods Employed in America for Experimental Investigation of Aerodynamic Phenomena at High Speeds." He illustrated his talk with a series of motion pictures which were prepared by the N. A. C. A.

Luis de Florez, Chairman of the Dinner Committee, and Charles L. Lawrance gave amusing talks on a new symbol which had been designed by Mr. de Florez to aid engineers in expressing an emotion which was quite common but hitherto had not been translated into mathematical form. It was termed a "multi-bellied Beta" and was for use when engineers reach a point in formulae when they endeavor to insert a noise resembling a Bronx Cheer. The members present gave a vote of appreciation to Mr. de Florez for his able arrangements for the Annual Dinner.

# Measurement of Aircraft Vibration During Flight

*Presented at the Engines and Propellers Session, Fourth Annual Meeting, I. Ae. S.*

C. S. DRAPER and G. P. BENTLEY, *Massachusetts Institute of Technology*


## SUMMARY

A JOINT instrument development program for the study of aircraft and engine vibration was entered into in 1934 between the Massachusetts Institute of Technology and the Bureau of Aeronautics of the United States Navy. The work consisted primarily of adapting well-founded principles, such as those of the seismic system and integrating circuit, and such standard equipment as amplifiers and oscillographs, to produce precision apparatus suitable for use in flight for the quantitative study of all types of vibration. The equipment developed to date consists of a pick-up unit for converting mechanical motion into electrical voltage variations, which are recorded photographically as a displacement-time record by means of a vacuum tube integrating amplifier and electro-magnetic oscillograph. Component parts of the instrument and the method of calibration are described; sample records and test results are presented.


Recent improvements in aircraft have produced an intense interest in vibration problems, because the exciting impulses from a high output power plant will often cause rapid structural failure due to vibration. Furthermore, other phases of the general problem are sufficiently well in hand for vibration difficulties to become important by comparison. The complicated nature of the systems which vibrate in aircraft makes it essential to study the problem with the aid of quantitative data taken in actual flight by means of equipment specially adapted to the problem. The actual work here reported was done at the Massachusetts Institute of Technology by the writers under the general supervision of Commander R. D. Weyerbacher (CC) U. S. Navy, and Dr. J. C. Hunsaker. Professors C. F. Taylor and E. S. Taylor gave valuable advice in the course of this development.

A satisfactory instrument for aircraft vibration work must have certain characteristics: (1) it must be sufficiently rugged to maintain its calibration over reasonably long periods of operation; (2) it must be sensitive enough to give quantitative results with the amplitudes which exist in aircraft work; (3) the sensitive units must be so small that they do not appreciably affect the vibration characteristics of the member to which they are attached; and (4) the recording system must be such that it can be operated at a distance from the point at which the vibration is to be measured.

Some parts of an aircraft, such as the engine crankshaft, are especially subject to torsional vibration, while the vibration of structural members will consist largely of linear components. On this account equipment for a complete vibration study must include pick-up units for both torsional and linear vibration. The advantage of apparatus constructed so that the same recording system can be operated by all types of pick-up units is obvious. With this in mind, the M.I.T. Vibration Apparatus is so designed that records from a number of separate pick-up units can be conveniently taken with a single recording unit. The record is a photographic trace showing the variation of vibration displacement or vibration velocity with time.

A photographic oscillograph operated by an electrical transmitting system is the most convenient means for transferring high frequency mechanical vibrations into a permanent record. The oscillograph may be either of the cathode ray type or electro-magnetic type. The cathode ray instrument would be superior if very high frequencies were encountered in aircraft work. However, since a frequency range of five to one thousand cycles per second will cover all practical cases, any good commercial electro-magnetic oscillograph will fulfill the requirements. Consequently, the simpler and more compact photographic system possible with an electro-magnetic oscillograph led to the adoption of this type for the M.I.T. Recording System.

Several methods are possible for transforming motion into electrical changes. Of these methods, the generator principle of electro-magnetic induction is well suited for use in the small rugged pick-up units required in studies of aircraft vibration. An induced voltage type of pick-up unit has the advantage that the record does not depend upon an accurate adjustment of the relative position of parts within the unit. However, the induced voltage output is proportional to the instantaneous velocity of the vibrating member so that an integrating circuit must be included in the system if the oscillograph is directly to record displacement. The integrating circuit reduces the voltage output available for operation of the oscillograph but a minor change in the vacuum tube amplifier is sufficient to compensate for the integrating circuit loss.

Fig. 1 is a diagram showing the essential parts of the equipment arranged to measure torsional vibration in an engine crankshaft. Measurements of any type of vibration may be carried out by substitution of the proper pick-up for the crankshaft unit.

## PICK-UP UNIT

The Pick-up Units are of the "seismic" type and utilize a mechanical principle commonly found in torsio-

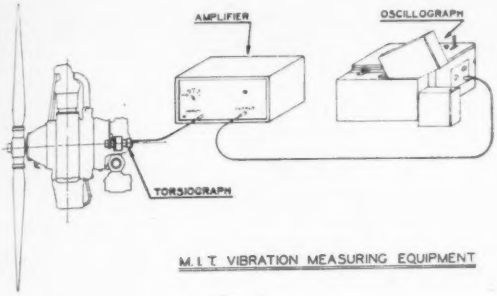


FIG. 1

graphs and linear vibration meters. The Air Corps Materiel Division Torsiograph which has been much used in recent years for studying crankshaft torsional vibration is an instrument of the "seismic" type.

In each Pick-up Unit a "supporting element" is connected rigidly to the part whose vibration is to be studied, while a mass called the "seismic element" is free to move in one dimension with respect to the supporting element except for a spring coupling and a damping arrangement. The spring coupling is made so weak that it will not transmit the vibration to be recorded. Under these conditions, the electrical system measures and records the relative displacement between the seismic element and the supporting element and hence the vibration displacement. Some slight damping action is necessary in order to prevent the natural frequency of the seismic element and its driving springs from appearing on the record.

### LINEAR VIBRATION PICK-UP

The essential parts of the M.I.T. linear vibration pick-up unit are shown in Fig. 2. The outer case of the unit serves as the supporting element which carries the seismic element, *S*, guided by the small rods, *R*. Elastic coupling between the case and the seismic element is supplied by the springs, *K*. The required damping action is obtained by friction between the case and the seismic element. The seismic element is made up of a permanent magnet, *M*, and an annealed iron structure which serves to set up an intense field in the annular gap, *G*. A coil of fine wire, *C*, is fastened rigidly to the case and projects through the gap, *G*. The coil extends well beyond the limits of relative motion so that the total amount of magnetic flux passing through the winding is constant.

With the unit mounted on a vibrating member, relative motion between the case and the seismic element induces a voltage in *C* which is proportional to the vibration velocity.

### TORSIONAL VIBRATION PICK-UP

The torsional vibration pick-up is similar in principle to the linear vibration pick-up; the seismic element is a heavy brass cylinder carried by a supporting element

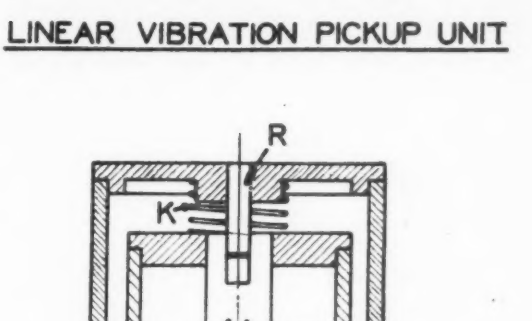


FIG. 2

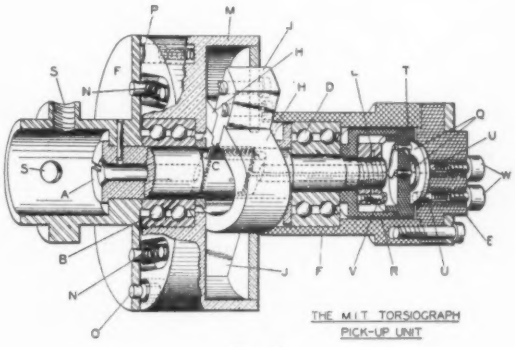


FIG. 3

concentric with the vibrating shaft and the electro-magnetic system is sensitive to angular velocity instead of linear velocity.

Fig. 3 is a diagram of the M.I.T. Torsional Vibration Pick-up. The supporting element is the shaft, *A*, which can be connected to a vibrating shaft by means of the flange, *F*. The coupling springs are shown at *N*, while the necessary damping is produced by a bakelite plug, *P*, which is forced against the flange by a spiral spring.

Magnetic flux is supplied by permanent horseshoe magnets which are carried in the seismic element, *M*. These magnets maintain a high flux density in the pole pieces, *J*. An iron armature carrying a coil, *C*, is fitted into a slot in *A*. This armature is so proportioned that a relative angular displacement between the seismic element and the supporting shaft produces a transfer of flux across the coil slot in the armature without affecting the flux density. In passing from one side of the coil to the other, the flux must cut the winding and

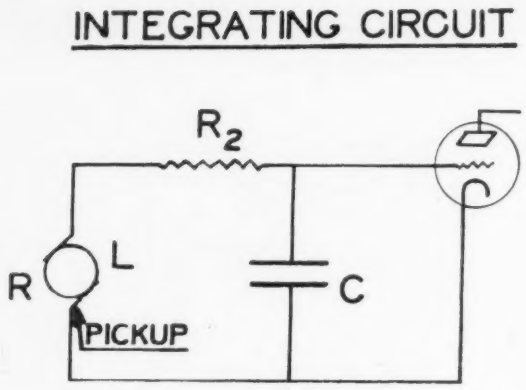


FIG. 4

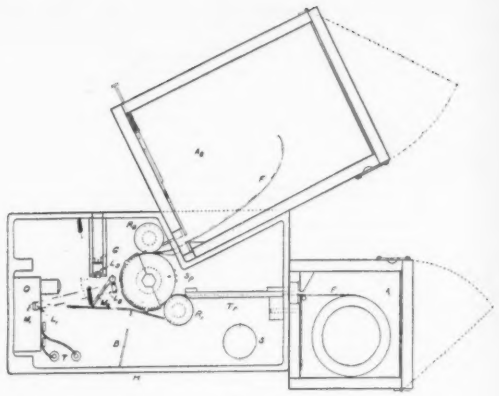

FIG. 5

consequently must induce a voltage in the coil proportional to the relative angular velocity. This induced voltage applied to the oscillograph through an integrating amplifier serves to produce a record of torsional vibration amplitude.

### SLIP RING SYSTEM

Since the unit itself rotates with the shaft under examination, it is necessary to use slip rings and brushes for coupling the pick-up to the amplifier. Such an arrangement would introduce irregular resistance changes in the output circuit of the pick-up unit if the recording system had a resistance of the same order of magnitude as the brush resistance variations. This difficulty is overcome by connecting the pick-up unit to a circuit whose resistance is very high compared to the possible changes of resistance due to the brushes.

### INTEGRATING CIRCUIT

The action of the integrating circuit depends upon the fact that the voltage across the terminals of a condenser is proportional to the time integral of the current flowing into the condenser. Thus if the current flowing into a condenser is made proportional to the output voltage from a pick-up unit, the amplified voltage across the condenser will produce a record of vibration displacements.

The essentials of an integrating circuit connected to a pick-up unit are indicated in Fig. 4.

Since any vibration may be represented by the simple harmonic components of a Fourier Series, it is sufficient to carry through the analysis for a single sinusoidal vibration with an arbitrary circular frequency $\omega$.

For this frequency the current in the circuit of Fig. 4 will be

$$i=\frac{e}{\sqrt{R^2_2-\left(\omega L-\frac{1}{\omega C}\right)^2}} \qquad (1)$$

or, if $R_2$ and $C$ be made large, and $L$ is small, the current as a function of the vibration velocity, $V$, and the pick-up "sensitivity constant", $K$, becomes to a good approximation:

$$i=e/R_2=KV/R_2 \qquad (2)$$

The voltage across the condenser terminals at any instant, $t$, is then:

$$E_c=\frac{1}{C}\int_o^t \mathrm{i}\,\mathrm{dt}=\frac{K}{CR_2}\int_o^t \mathrm{v}\,\mathrm{dt}=\frac{K}{CR_2}\,X \qquad (3)$$

where $X$ is the displacement at the time $t$ due to vibration.

It is apparent from Eq. (1) that the integration process will become more accurate as the resistance, $R_2$, and the capacity, $C$, are made larger. On the other hand, Eq. (3) shows that the voltage which is available across the condenser for operating an amplifier becomes smaller as $R$ and $C$ are increased. In any actual case the design must be a compromise between these two opposing tendencies. Fortunately, the output voltage available from an induced voltage pick-up is so large that good results can be obtained from a relatively simple amplifier.

### THE RECORDING SYSTEM

The Recording System consists of a high-fidelity amplifier to provide sufficient current for operation of the electro-magnetic type oscillograph employed and a photographic system for obtaining a continuous record of the oscillograph trace. The amplifier uses two stages of voltage amplification resistance-capacity coupled, driving push-pull power tubes in the output stage. In order to eliminate extraneous effects from changes in supply line voltage, a battery plate supply is used on the first two stages.

The power output tube plate supply is rectified alternating current. These tubes are transformer coupled to the oscillograph element, providing a high driving current and at the same time eliminating the necessity

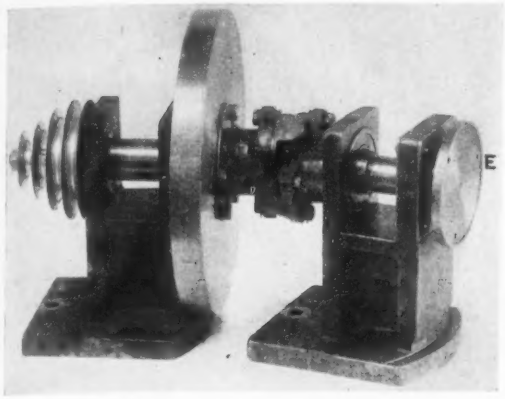


FIG. 6

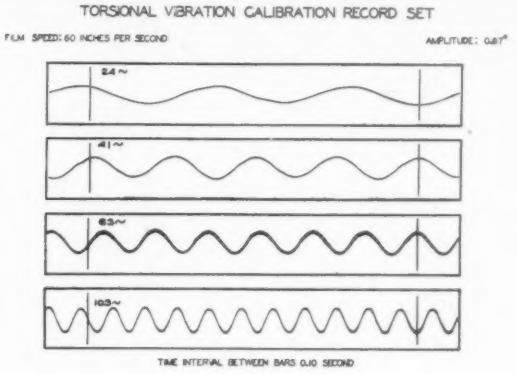


FIG. 7

of "bucking" direct current components out of the element. The entire amplifier-oscillograph combination is stable and requires no adjustments.

A special oscillograph camera unit, illustrated in Fig. 5, is used for photographic recording. Standard 35 mm. motion picture film passes from the film supply box, $A_1$, through the guide, $T_r$, and over the sprocket, $S_p$, into the receiving box, $A_2$. The film is held against the sprocket by rollers. The sprocket is driven through a gear train and friction clutch from a synchronous motor. This arrangement permits a choice of film speeds. The film is accelerated to the desired speed within a very short distance by allowing the motor to attain synchronous speed before releasing the clutch.

The optical system uses a straight filament incandescent lamp, $S$, for supplying light to the mirror, $M_1$, in the high frequency oscillograph element. A high intensity spot from $M_1$ is formed on the motion picture film by means of the spherical lens, $L_1$, and the cylindrical lens, $L_2$. For visual examination of the light spot, mirror $M_2$ may be swung downward into the path of the light beam, as shown in the Figure, so that the spot will be formed on the ground glass, $G$, by the cylindrical lens, $L_2$.

A convenient arrangement makes it possible to take an oscillograph record by the operation of a single control.

## TORSIOGRAPH CALIBRATION

In order that torsiograph records may be interpreted quantitatively, it is necessary that some standard source of torsional vibration be used for calibration purposes. To simulate conditions of actual operation, the torsiograph calibrator of Fig. 6 was designed to superimpose an almost sinusoidal torsional vibration on a steady rotation. The unit consists of a well-made Hooke's joint carrying a flywheel on the driving end and a fitting for the torsiograph on the driven end. An adapter fitting replaces disc, $E$. By setting the cast-iron pedestals so that the driven shaft is at an angle with the driving shaft, a known vibration amplitude may be introduced into the motion of the driven shaft. The vibration amplitude is computed from geometrical considerations and checked experimentally by direct measurement. An uncertainty of about five percent in the amplitude measurements introduces an equal uncertainty in the absolute value of the torsiograph calibration.

In operation, the calibrator is driven from a variable speed electric motor, making it possible to explore the sensitivity characteristics over a sufficiently wide frequency range. The quality of the calibrator wave form may be seen from the records of Fig. 7.

It is necessary that the entire torsiograph equipment operate without serious distortion over a frequency range of 10 to 1,000 cycles per second. It can be shown that with proper damping the system consisting of pick-up unit and integrating circuit has a constant sensitivity at frequencies above about six times the natural frequency of the seismic element. These characteristics simplify calibration, since it is only necessary to explore the frequency range from one to ten times the natural frequency of the seismic system with the calibrator.

For frequencies greater than 100 cycles per second it can be shown that the output voltage of the combined pick-up unit and integrating circuit is directly proportional to amplitude of vibration. Consequently, any distortion in the record will be due to the amplifier-oscillograph system; calibration of the equipment above 100 cycles per second, therefore, reduces to a study of electrical characteristics by means of a standard vacuum tube oscillator. The response of the amplifier-oscillograph system so measured is shown in Fig. 8. The sensitivity of the equipment is decreased somewhat at low frequencies due to the use of coupling condensers and output transformer; the effect of galvanometer resonance is apparent in the increased sensitivity at about 4,000 cycles and the rapid decrease in response at higher frequencies.

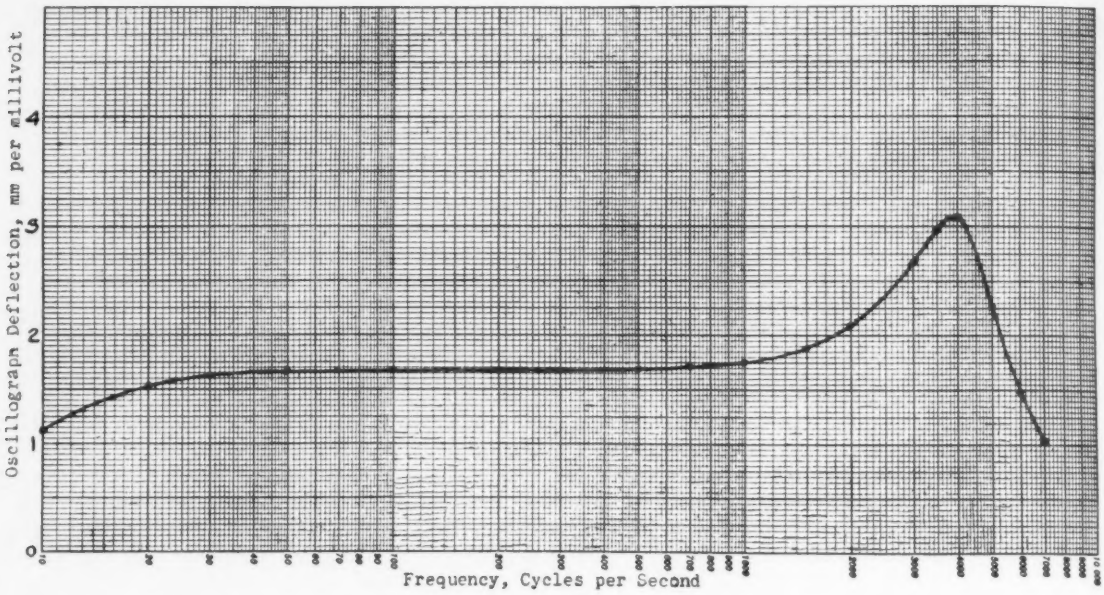


FIG. 8. M. I. T. Amplifier-Oscillograph Response. Oscillograph Sensitivity 122 mm./amp.

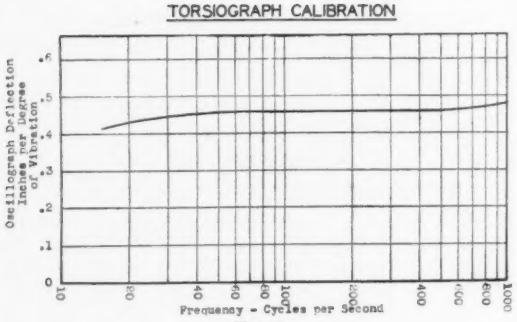


FIG. 9

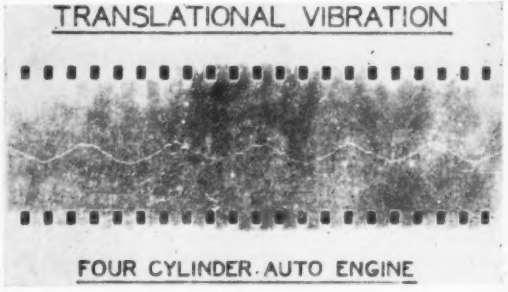


FIG. 10

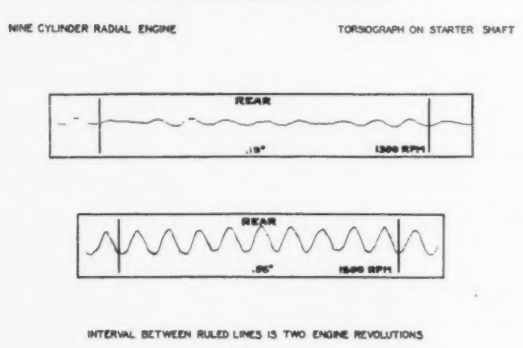


FIG. 11

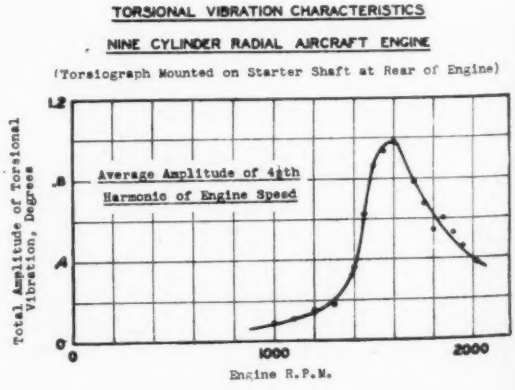
TORSIONAL VIBRATION CHARACTERISTICS
NINE CYLINDER RADIAL AIRCRAFT ENGINE
(Torsiograph Mounted on Starter Shaft at Rear of Engine)
Average Amplitude of 4th Harmonic of Engine Speed
Total Amplitude of Torsional Vibration, Degrees
0
1000
2000
Engine R.P.M.

FIG. 12

The final calibration step consists of combining the direct mechanical calibration of the entire system for frequencies up to 100 cycles per second with the curve of Fig. 8 for the amplifier-oscillograph system at the higher frequencies to obtain the overall calibration curve of Fig. 9. The opportunity to depart from mechanical methods of calibration at the higher frequency range where their reliability becomes doubtful provides a dependable calibration over a range much greater than is likely to be encountered.

### Performance Tests

A sample record of translational vibration is shown in Fig. 10. This is a velocity record of an automobile four-cylinder engine taken in early 1934.

Sample torsional vibration records taken in flight at the rear of the crankshaft of a nine-cylinder single-row radial engine are reproduced in Fig. 11 for a speed near resonance and another well away from the critical.

A series of records taken at various engine speeds provides the data necessary for making a resonance plot like Fig. 12. The same result may be obtained with less experimental difficulty by making a single record while the engine is accelerating from idling speed to full throttle speed.

## Fourth Annual Meeting of the Institute of the Aeronautical Sciences

### Technical Sessions

The Fourth Annual Meeting of the Institute of the Aeronautical Sciences was held in the Pupin Physics Laboratories of Columbia University, New York City, on Wednesday, Thursday and Friday, January 29–30–31, 1936. The facilities of the Pupin Physics Laboratories and the Faculty Club were made available to the Institute through the courtesy of Columbia University and of Professor George B. Pegram of the Physics Department.

During the three days of the meeting an Apparatus Exhibit was held in the Pupin Physics Laboratories. Members and their guests had the opportunity of inspecting some of the latest developments in the aeronautical field.

The program of the Fourth Annual Meeting was arranged somewhat differently from that of the Third Annual Meeting. In the morning, short papers were presented. In the afternoons surveys of specialized fields were given and an attempt was made during the discussions to estimate the state of knowledge and the avenues of research that appeared to be most useful for future progress.

The Annual Meeting of the members of the Institute was held at 5 o'clock on Wednesday afternoon, and the Annual Dinner at 6:30 Thursday. Accounts of the Annual Meeting and the Annual Dinner appear elsewhere in this issue.

Over four hundred members and guests attended the meetings and the dinner.

The Technical Sessions of the meeting covered a three-day period, beginning at 10 o'clock each morning and continuing until 12:30, when the members lunched at the Faculty Club. The Sessions were then resumed in the afternoons.

The program for these three days covered a wide range of professional interests and is much too extensive to be fully reported in this issue of the Journal.

Interesting and significant views on the present status and trends of our knowledge in the field of the aeronautical sciences were developed by the papers presented in the morning sessions and in the afternoon discussions. While most of these papers and discussions have been submitted for publication, it is impossible to present all of them in this one issue of the Journal. As far as practicable, therefore, papers and discussions of the sessions on engines and propellers are presented here. Subsequent issues of the Journal will contain further papers and digests of the other sessions.

The Editor also wishes to inform readers of the Journal that no reprints or additional material in reference to articles or digests printed in the Journal are available. All inquiries for further information about articles or digests should therefore be addressed directly to the author.

# Factors Affecting the Cost of Airplanes

*Presented at the Aircraft Operations Session, Fourth Annual Meeting, I. Ae. S.*

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## INTRODUCTION

THIS subject is one which can always be relied upon to start a discussion whenever it is raised in aircraft circles. Great differences of opinion will be voiced as to the relative importance of various factors, depending somewhat on whether the discussion is between persons in the industry who are engaged in sales, engineering, design or factory work. The attitude of those outside the industry is usually quite supercilious with the intimation present that everyone engaged in the design, development, or construction of airplanes is a sort of prima donna. Therefore, because of the rather hazy information which seems to surround the subject, it appears in order to discuss the problems from several points of view in an effort to arrive at logical conclusions.

The effect of quantity production on cost, particularly, requires study as in this respect more than in others, there exists a lack of appreciation of the variation which occurs. Recently the matter became of increasing interest and importance because of the program sponsored by the Bureau of Air Commerce for the development of a small two-place airplane which, it was hoped, could be marketed at $700 assuming a quantity of ten thousand units could be released for construction.

The present writer started his studies of the variation of cost with quantity in 1922. A curve depicting such variation was worked up empirically from the two or three points which previous production experience of the same model in differing quantities made possible. Through the succeeding years, this original curve, which at first showed the variation in labor only, was used for estimating purposes and was corrected as more data became available. The form which this curve takes when plotted on plain cross-section paper is shown in Fig. 1. On this figure there is also shown the variation of the ratio of labor to raw material as quantity varies. The correcting of curves of this type by new points of actual experience resulted in data which permitted other curves to be plotted, showing the variation of raw material, purchased material, and finally, of the whole airplane, against quantity.

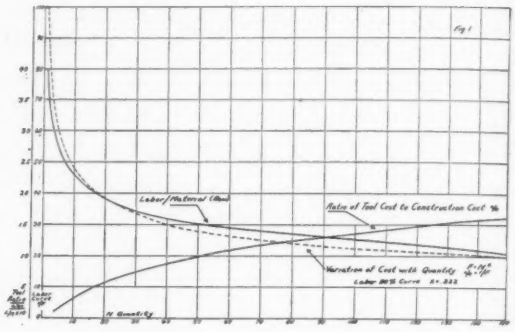


Fig 1

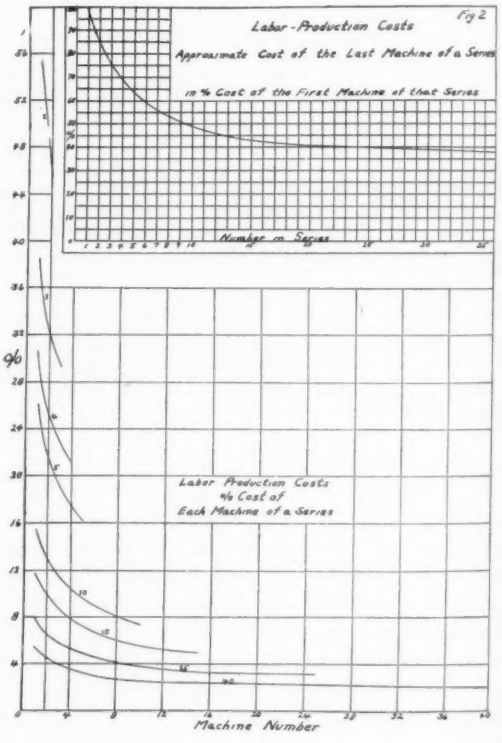


Fig 2
Labor-Production Costs
Approximate Cost of the Last Machine of a Series
in % Cost of the First Machine of that Series
Number in Series
Labor Production Costs
% Cost of
Each Machine of a Series
Machine Number

Effort was also made to plot the cost of each machine of a series in percent of the total cost of the series for varying quantities. The work along this line is shown in Fig. 2 which, however, must be considered as more approximate in accuracy than the others because of the greater difficulty in securing reliable empirical information on the relative cost of each machine of a series, since accounting methods seldom reveal such data. However, the curves of Fig. 2 are believed to show the general shape of curves and trend of data of this kind.

## Design Factors

Type of construction is obviously one factor which governs cost. Design not only affects relative cost in a given quantity but also may affect the shape of the curve which shows the variation of cost with quantity.

In the early days, the so-called stick-and-wire-and-fabric construction maintained, using wooden members for beams and struts with metal fittings at the joints and wires as truss members. This type of construction was eminently suited to quickly and cheaply constructing a prototype machine. It also proved economical in quantities which have maintained for airplane construction up to the present time. In spite of the inherent cheapness which this type of construction permits in small quantities, it is somewhat doubtful as to whether or not so steep a curve of cost reduction for increasing quantity would maintain for this type when compared with others.

Next there was a prevalence of the use of welded steel tubing in lieu of the stick-and-wire construction, almost exclusively in the fuselage and extensively, but somewhat less, in the tail surfaces and wings. Fabric was still used as a covering and wooden beams were the rule. This type of construction permitted the use of jigs and fixtures which, when any reasonable quantity was involved, allowed quite cheap construction. The operation of welding, however, was one which in large quantities could not progress in time saving beyond a certain point. The chief gain, therefore, in reducing production costs was in the use of better tools and fixtures rather than anything inherent in the construction which lent itself to progressively cheaper fabrication in large quantities.

Finally, we have come to the general use of monocoque construction wherein sheets of relatively thin material are formed and attached together by rivets. This is a type of construction which to an even greater extent requires the use of proper tools and fixtures for cheap quantity production and, partly for this reason, is relatively expensive in prototype or small quantities. For constructing a prototype airplane it is estimated that the use of monocoque construction increases its cost, when compared to the older types, by from fifty to one hundred percent. This same ratio holds in small quantities but in larger quantities greatly decreases and in very large quantities would, it is believed, indicate the reverse in tendency as to labor costs.

The cost of raw materials used in monocoque construction is only slightly more than in the older types. For an all-metal plane of alclad, it appears that an average price of sixty cents per pound of material purchased will hold for the sheet metal used and about one dollar per pound for the sum total of castings, rivets, extruded sections, etc. For all the metal used, a price averaging about seventy-one cents per pound of material purchased is about what will maintain. When considering the whole structure of the airplane, this figure increases to about one dollar a pound, as other parts, such as wheels, oleo struts, and purchased items on which labor is expended by some vendor will average higher than raw metal. This figure, in turn, must be increased for factor of waste when determining the price per pound of "finished product" instead of "material purchased," arriving at a figure of about one dollar and a quarter per pound for the whole airplane and ninety cents per pound for metal only (assuming a quantity of about twenty-five units).

Now let us compare material costs of all-metal construction to material costs of tube, fabric and wood construction. As a guide it should be noted that airplane spruce is by no means cheap and has a high waste percentage. Cost of dope, paint and fabric is also relatively high. Assuming, therefore, that the cost of materials is only slightly more (if any) for all-metal construction than for the older types (and actual records bear this out), it is important to note that in very large quantities the prospect of obtaining the hoped for cheap monocoque construction is satisfactory from this standpoint because of the relatively greater importance of material as compared to labor as quantities increase. This will be more clearly seen by referring to the labor/material curve in Fig. 1 where the ratio is reduced from about four to one in a quantity of one ship to about one to one in a quantity of one hundred and fifty ships.

Labor involved is, for the most part, a matter of joining. As mentioned before, welding is not particularly economical from this standpoint and particularly is not susceptible of great time savings in mass production. Riveting is also extremely expensive at the present time but is sufficiently better adapted to tooling and further developments in automatic riveting machines so that for large quantities in the future it holds good prospects of being accomplished economically. Spotwelding has a great deal of merit as a cheap method of joining parts and the rapid strides now being made in the development of electric spotwelding equipment for use in joining aluminum alloy parts is encouraging. The use of stainless steel (spot welded) possesses the same promise from the cost standpoint although its general adaptation from the standpoint of design efficiency is still open to question, except perhaps for limited application.

It therefore appears that the present trend towards the use of monocoque construction for all parts of the airplane is efficient from the structural, weight and aerodynamic considerations and may also be expected to show good results from the cost standpoint when construction is undertaken in really large quantities.

Naturally, such generalities as simplicity of design, reduction of parts, design of simple parts, and use of forgings must, as design factors, be applied to any type of construction in order to attain economy. In addition to the trend in material costs and riveting time reductions applied to monocoque construction, the possibilities

of stamping large contours in various types of dies fitted to large presses represents a means of labor saving for this type of construction.

### Tooling

In Fig. 1 a curve is shown which indicates the trend of relative tool costs plotted against production quantity. The tooling factor and the susceptibility of a given type of construction to the use of tools is important in deriving the slope of the production curve. Many of the factors of the different types of construction discussed have been mentioned in connection with their susceptibility of tools application.

From the design standpoint, sight has frequently been lost of the need for considering future tooling at the time parts are drawn. This particularly applies in the case of forgings where, when production orders are received, it is frequently necessary to re-design large numbers of parts in order to substitute forgings for built-up construction. Analysis has shown that contrary to popular belief, the quantity of parts necessary to make a forging die pay is quite small. It is usually possible, in an order of twenty-five ships to use forgings for a great many parts and if the quantity is one hundred ships, there are very few small parts which cannot economically be so made. In Fig. 5 there is shown a photograph of a number of forgings used on a plane manufactured in a quantity of fifty units. In every case, an analysis was made of the exact saving involved before the forging was decided upon. The results were extremely gratifying.

### Changes

The tremendous cost of changes introduced into a production order during construction is too well known to require emphasis. This cost is involved, not only in shop delays but in the engineering expense of re-designing. It is appreciated that in a rapidly moving art such as aviation, changes are more or less inherent. However, as standardization of type construction becomes more general, it may be expected that less changes will be required during production runs in the future. In using the curve developed in this paper, it should be recognized that the factors derived are based on the assumption that no major changes will be introduced during construction.

### Effect of Size

The factors which apply when considering the effect on cost of size and which favor decreased cost with increased size are the following:

First, the number of parts does not increase proportionately to size increase. Next, in a large airplane, there are less parts of minimum size and gauge, thus favoring ease of handling to some extent. Next, within certain limits, there may be expected to maintain a slightly smaller unit weight as size increases. It is appreciated that the so-called square-cube rule will enter in at some stage, invalidating the above statement. However, the effect of this rule is counterbalanced by the structural inefficiency of minimum gauges used in small airplanes and of the greater spread in large airplanes per unit of structural weight for such items as crew, radio, instruments, etc. Also, there should be mentioned the fact that there is better access to parts in large machines than maintains in the cramped quarters of small ones.

On the other hand, there is the greater handling labor of very large units in assembly which is decidedly more than in small machines.

All in all, it is believed that when measured in dollars per pound of structural weight there will be a decreasing cost for machines up to about twenty-five thousand pounds with a very gradual increase above that figure.

### Effect of Quantity

The factors which make possible cost reductions with increase in the quantity produced are as follows:

#### Labor

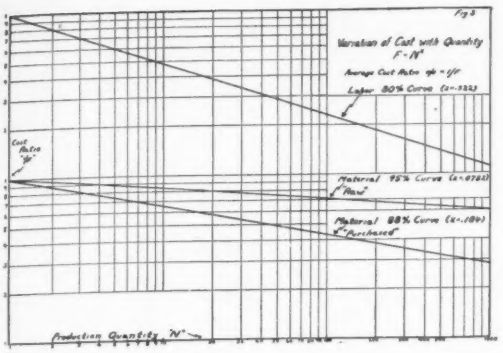
The improvement in proficiency of a workman with practice and particularly if time studies for economy of motions are made, is well known. This applies particularly in assembly operations but also holds for other types of work. It may also be anticipated that there will be less changes to disconcert the workman as the quantity increases. Another factor is the greater spread of machine and fixture set up time in large quantity production. As previously mentioned, one of the principal factors is the economy of labor which greater tooling can give as the quantity increases. A final factor allied to the one last mentioned, is the ability to use less skilled labor as more and more tooling and standardization of procedure is introduced.

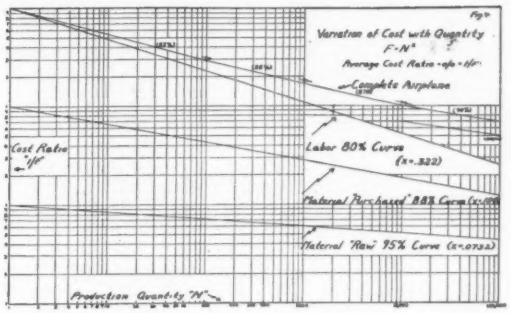
In developing the curve which shows variation of labor cost with production quantity, it became evident that its form was of the type depicted by the formula $F = N^X$. This resolves into an expression for $X$ as follows:

$$X = \frac{\text{Log } F}{\text{Log } N}$$

Where $F$ = a factor of cost variation proportional to the quantity $N$. The reciprocal of $F$ then represents a direct percent variation of cost vs. quantity.

A curve may be plotted which shows directly the relationship between the two variables and when plotted on log-log paper, it becomes a straight line. In Fig. 3 such a curve appears; there called the eighty percent curve which is represented by a value of .322 for the exponent $X$ in the above formula. This "eighty percent" has a definite meaning in that it represents the factor by which the average labor cost in any quantity




shall be multiplied in order to determine the average labor cost for a quantity of twice that number of airplanes. On Fig. 3 the curves are so plotted as to be susceptible of use for quantities which are likely to maintain for some time to come. On Fig. 4 the paper is arranged to carry the numbers in production to very large amounts, of particular interest in noting the possible future of airplane costs and of use in making certain comparisons mentioned further along.

### Material

Material also decreases in cost as quantity increases due to the following reasons:

First, the amount of waste is cut down. When comparing the light weight of the structure of the airplane with the actual weight of material purchased in order to construct it, it has been found that in a quantity of one to five units this waste is as large as forty percent. It reduces rapidly as quantity increases, to twenty-five or thirty percent in quantities of twenty-five to fifty units and down to twenty percent in a quantity of one hundred units. Greater cutting efficiency and more economical purchasing from the standpoint of matching parts from sheets of a given size partially explain this reduction. Then too there is also a reduction in material cost with quantity due to the reflected effect of the reduction of labor which at various stages has been applied by some vendor to what we here call material. In addition, there is the prospect of greater discounts when purchasing in large quantities.

In the graphs shown in Figs. 3 and 4, the curve for material reduction applying to raw material is given as a ninety-five percent curve (exponent of .0732). For purchased material this factor is shown at eighty-eight percent (exponent of .184). By purchased material is meant such items as wheels, oleo struts, instruments, engines and starters, and accessories of a nature usually procured from outside by airplane manufacturers. The change in factor to eighty-eight percent instead of ninety-five percent when comparing purchased raw material is brought about by the greater proportion of labor present in the former. The item of purchased material (and particularly for engines, propellers, and instruments) is, in reality, not truly represented by a straight line in quantities up to one or two hundred as shown in Fig. 3 and as used by an airplane manufacturer in that the purchased material vendor is the supplier to many airplane manufacturers and thus is constantly manufacturing in greater quantities than is the airplane manufacturer. It should also be noted that frequently the same purchased item is used several times in one airplane, further emphasizing the above principle. Nevertheless, if intelligent allowance of this fact is made for special cases, the curves may be used satisfactorily. In the preparation of actual estimates it is best to make a third material item of engines, propellers, and instruments using prices received from actual quotations only reduced by the amounts obtainable from discounts securable after negotiation with the vendor, noting however from the general principles of the curves, the nature of reductions in large quantities which it is reasonable to expect.

### Overhead

The overhead, or burden, varies, within limits, with quantity. The exact amount fluctuates greatly for different cases, depending, for example, on whether a particular factory is engaged in the manufacture of one type of plane or of many types. The following relationship shows for one particular factory the type of overhead variation which maintains. When this factory was employing five hundred workmen, the overhead ran one hundred percent; at one thousand workmen, this was reduced to seventy-five percent; and at fifteen hundred workmen to sixty percent. It is probable that the curve would flatten out above that amount and then, in very large quantities, increase in amount. In combining factors of labor, material, and overhead to determine a suitable curve for direct application to the whole airplane, a figure of seventy percent for overhead has been used in this paper.

### Complete Airplane

In Fig. 4 there is shown a curve for use in comparing the cost of the complete airplane in different quantities.

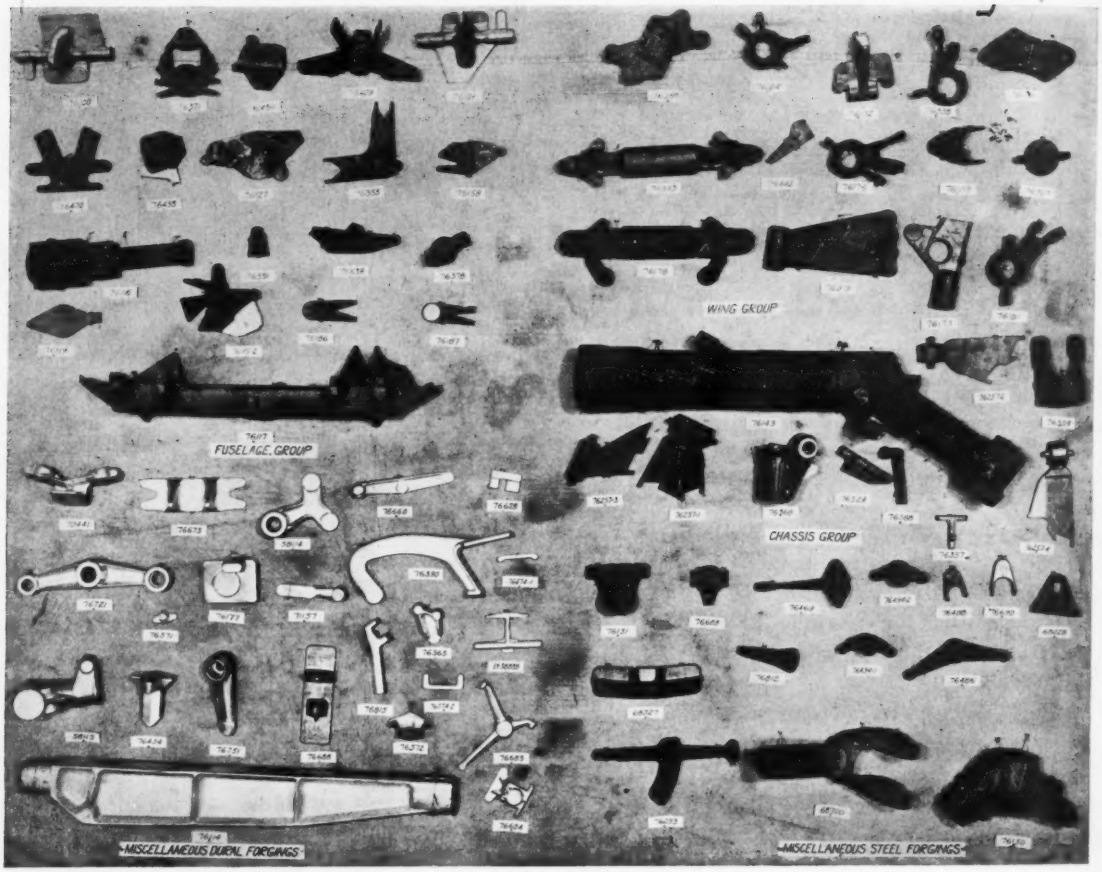



FIG. 5

A suitable relationship of labor, raw material, purchased material, and overhead has been used and by this method it is indicated that the curve will start out at eighty-three percent, then change to eighty-five percent, then change to eighty-seven percent, and finally reach ninety percent. This change in slope is an indication of the relatively greater importance of material to labor as quantity increases.

### Non-Consecutive Orders

Considerable judgment is necessary when applying the curves here developed to succeeding orders of the same airplane. Consideration must be given to the changes introduced between these orders and, as well, the lapse of time which occurs. It is obvious that new set ups; re-establishment of tools; labor turnover between orders; necessity for making new purchases; all contribute towards higher costs for the second order than would maintain if it were combined at one time with an earlier one. Judgment must therefore be used in selecting the proper factor when estimating the costs for such succeeding order. In general, and as an indication of procedure, the factor for the new order would vary from a factor proper for a quantity which equals the quantity of the new order plus eight-tenths of the quantity of the old order, to the factor for a quantity represented by the new order only if, in this case, the airplane has been out of production for a long time.

### UNIT COST

It is interesting to consider the cost per pound of structure or of airplane light weight (including engine, propeller, instruments, etc.) which now maintains and which may be expected to maintain when producing in increasing quantities. In quantities with which we are so far familiar, it appears that the *structure* of an airplane made by stick-and-wire-and-fabric or welded steel-fabric construction ranges from about three and one-half to four and one-half dollars per pound and for the *whole airplane* (light weight), including engine, propeller, and instruments, this figure ranges from four to five dollars per pound, in a quantity of twenty-five in each case. These figures for all-metal airplane construction range, for the *structure*, from five and one-quarter to six and one-quarter dollars per pound, and for the *whole airplane* (light weight), from five and three-

quarters to six and three-quarters dollars per pound. These latter figures for an all-metal airplane would reduce to about two and one-half and two and three-quarters dollars per pound in a quantity of one thousand. For one hundred thousand units (if we may be pardoned for mentioning a figure so out of keeping with experience to date) these values, respectively, would reduce to one dollar and one dollar and twelve cents per pound. It is interesting to compare this figure with the present cost of materials only ranging from just under one dollar per pound to about one and one-quarter dollars per pound as previously derived. The range of figures here mentioned are roughly applicable to all sizes and functions of machines, from the small two-place private owner plane to the large transport. However, note should be made of the fact that in quantity extensions it is the small plane for which the extremely large productions may be anticipated in spite of the fact that at present larger productions for transport planes than for the small ones maintain.

Also, it should be noted that other factors enter in when consideration is given to the unit cost of military planes constructed to government specifications and under government supervision. Numerous comparisons made in the past indicate that in this case the cost per pound when compared to equivalent weight of material for a commercial customer, has increased under government contracts by never less than fifteen percent and in certain cases to as much as thirty-five percent, averaging perhaps twenty percent. This increase is occasioned by the added complexity of the product; the need for following government specifications, handbooks, manuals and general requirements; the loss of smooth engineering and factory operations through government inspection requirements and the delays in receiving approvals of analyses, tests, drawings, and parts.

Let us now determine by actual example the anticipated variation in price with quantity. For the purpose we may select a two-place airplane somewhat along the lines of the specifications used by the Bureau of Air Commerce in recent purchases. The general specifications in the present example are as follows:

| | |
|---|---|
| Useful Load | 700 lbs. |
| Light Weight | 1100 lbs. |
| Gross Weight | 1800 lbs. |
| Structural Weight | 800 lbs. |
| Engine | 100 to 125 h.p. |
| High Speed | 125 to 150 m.p.h. |
| Speed Range | 3 |
| Material | All-Metal |

*Price Estimate in a Lot of 25*

| | |
|---|---|
| Cost—1,100 lbs. (Light Weight) @ $6/lb. | $6,600.00 |
| Profit (manufacturing, at 10%) | 660.00 |
| Sales Discount (20%) | 1,815.00 |
| Price | $9,075.00 |

(Use $9,000, as engine price will be lower in small quantities than is assumed in $6/lb. unit cost used above for light weight.)

*Chart of Price Variation*

| Quantity | 25 | 100 | 500 | 1,000 | 10,000 |
|---|---|---|---|---|---|
| Factor (%) | .43 | .29 | .20 | .168 | .10 |
| Price ($) | 9,000 | 6,070 | 4,180 | 3,520 | 2,090 |
| Price per lb. | 8.18 | 5.52 | 3.80 | 3.20 | 1.90 |

We thus see that for a plane of these specifications and in the original quantity cited by the Bureau of Air Commerce when commencing its $700 Small Plane program, would have to be priced at about three hundred percent more than was hoped. Perhaps some reductions from the estimate could be effected by altering construction, design, and reducing sales discounts and profits (although by so doing the ten thousand units would probably never be sold) but in the quantity of ten thousand units which is under consideration, it is doubtful whether a price of less than $1,750 could possibly be attained.

Let us now see what may be expected in the class of plane more nearly comparable in useful load to our present family automobile to ascertain what deductions seem justifiable. The general specifications of such a plane might be as follows:

| | |
|---|---|
| Capacity | 4–5 Place |
| Useful Load | 1400 lbs. |
| Light Weight | 2200 lbs. |
| Gross Weight | 3600 lbs. |
| Structural Weight | 1600 lbs. |
| Engine | 300–400 h.p. |
| High Speed | 175–200 m.p.h. |
| Speed Range | 3 |
| Material | All-Metal |

In estimating the price in a lot of twenty-five, we may assume a price just twice that used for the previous example as the light weights bear that relationship:

*Chart of Price Variation*

| Quantity | 25 | 100 | 500 | 1,000 | 10,000 | 100,000 | 250,000 | 1,000,000 |
|---|---|---|---|---|---|---|---|---|
| Factor (%) | .43 | .29 | .20 | .168 | .10 | .07 | .061 | .05 |
| Price ($) | 18,000 | 12,140 | 8360 | 7040 | 4180 | 2930 | 2550 | 2090 |
| Unit Price ($/lb.) | 8.18 | 5.52 | 3.80 | 3.20 | 1.90 | 1.33 | 1.16 | .95 |

Let us now see where the automobile stands as to price in approximately these quantities:

| | | | | | |
|---|---|---|---|---|---|
| Price ($) | 4,700 | 1,200 | 1,000 | 750 | 650 |
| Weight (lbs.) | 6,000 | 3,700 | 3,400 | 3,250 | 2,900 |
| Unit Price ($/lb.) | 783 | .324 | .294 | .231 | .224 |
| Ratio of Unit Prices:— Plane to Automobile | 4.1 | 5.86 | 4.53 | 5.02 | 4.28 |

Some conclusions from a study of this comparison are of interest, even though the values are extremely approximate in nature.

First, it will be noted that the downward trend in prices of cars with quantity indicates a curve relationship approximating that used for the plane, as shown by the fairly constant ratio of costs per pound in different quantities which maintain. This ratio averages about 4.75. This increase in unit cost of 475% for the plane over the car is occasioned by three causes: the improvement in weight saving of fifty percent as indicated by comparing light weights (2200 lbs. vs. 3300 lbs.) with the attendant design refinement and more expensive construction; next, the increased complexity inherent in three dimensional vs. two dimensional operation, which necessitates more controls, more strength stipulations and the use of seventy-five horsepower per person against about twenty-five; and finally, by the greater efficiency in designing cars to low cost because of the vast backlog of experience in the art not yet acquired or directly applicable to planes in large quantities. In this last item lies the hope of "beating the curves" if and when we get into large production.

The account is not all one-sided however, as will be seen by examining performance. In fact a true evaluation of the saving in time, in an age wherein this factor is of ever increasing importance, should and, it is believed will, throw the balance the other way for many uses. The plane has a cruising speed of three times that of the car (175 vs. 57 m.p.h.) and, when comparing time saving in making a trip between points three hundred air miles apart, is five times superior (300 air miles at 150 m.p.h. equals 2 hours as against 400 road miles at 40 m.p.h. equals 10 hours). Only time can prove just how valuable time saving is to mankind.

## Market

All of the foregoing, in reality, has been carried through in an effort to establish the market possibility which price reductions will make feasible. We have the usual circle of relationships wherein price can be reduced most effectively by increasing quantity but wherein quantity production can only be obtained through market possibilities brought about by cheaper prices.

Simplicity and cheapness of design will make possible gradual reductions in prices which will make possible the sale of somewhat greater quantities with cheaper prices brought about by virtue of such quantity increase. The desirable cycle of events can be given greatest impetus by improving the product which means improvement in performance efficiency and safety, so as to make it possible to offer the public something really worth while. As the benefits of flying are more and more realized because of the use by the public of airplanes of surpassing performance and far greater safety, the possibilities of market extension alluded to will be realized.

Acknowledgment is made of the great assistance during the past fifteen years rendered by my associates, Mr. E. Bertran, Mr. F. W. Devlin, and Mr. J. A. Williams.

## Chart of Price Variation

*Assumed Airplane—Specifications*

| | | | |
|---|---|---|---|
| Capacity | 4–5 Place. | Engine | 300–400 h.p. |
| Useful Load | 1,400 lbs. | High Speed | 175–200 m.p.h. |
| Light Weight | 2,200 lbs. | Speed Range | 3. |
| Gross Weight | 3,600 lbs. | Construction | All-Metal. |
| Structural Weight | 1,600 lbs. | | |

*Unit Airplane Prices*

| Quantity | 25 | 100 | 500 | 1,000 | 10,000 | 100,000 | 250,000 | 1,000,000 |
|---|---|---|---|---|---|---|---|---|
| Factor (%) | .43 | .29 | .20 | .168 | .10 | .07 | .061 | .05 |
| Price ($) | 18,000 | 12,140 | 8360 | 7040 | 4180 | 2930 | 2550 | 2090 |
| Unit Price ($/lb.) | 8.18 | 5.52 | 3.80 | 3.20 | 1.90 | 1.33 | 1.16 | .95 |

*Rough Automobile Data*

| | | | | | |
|---|---|---|---|---|---|
| Weight (lbs.) | 6,000 | 3,700 | 3,400 | 3,250 | 2,900 |
| Price ($) | 4,700 | 1,200 | 1,000 | 750 | 650 |
| Unit Price ($/lbs.) | .783 | .324 | .294 | .231 | .224 |
| Ratio of Unit Prices Plane to Auto | 4.1 | 5.86 | 4.53 | 5.02 | 4.28 |

*Notes:*

1—Average Ratio Unit Price Plane to Auto is about 4.75.
2—Small fluctuation from average Unit Price Ratio indicates similar auto production curve.
3—Airplane has greater weight economy (50% lighter than auto).
4—Airplane has 75 h.p. per person, Auto 25.
5—Plane Cruising Speed vs. Auto equals 175/57=3:1.
6—Plane Block-to-Block Time for 300 air miles vs. auto equals 10 hrs./2 Hrs.=5:1.

# Harmonic Analysis of Engine Torque Due to Gas Pressure

*Presented at the Engines and Propellers Session, Fourth Annual Meeting, I. Ae. S.*

E. S. Taylor and E. W. Morris, *Massachusetts Institute of Technology*

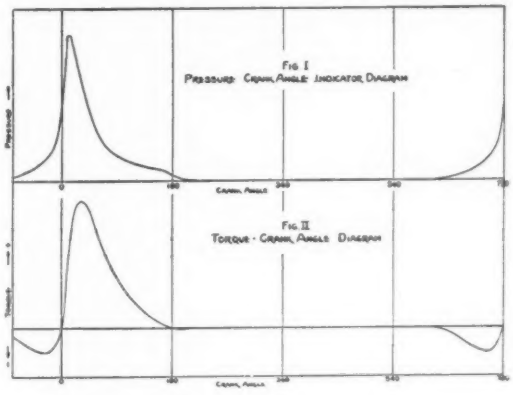
IN order to determine the vibration of a body such as an airplane engine, it is necessary to know "forcing function," or unbalanced forces and torques acting upon the body as well as the mass and elastic characteristics of the body and its supporting structure. In the airplane engine, the unbalanced torque about the crankshaft axis is one of the most troublesome components of the forcing function. It causes vibration of the engine as a whole, as well as vibration of the elastic system comprising the crankshaft and propeller. The variation of torque with crank angle is due partly to the change in kinetic energy of the reciprocating and oscillating engine parts, and partly to the gas pressure upon the piston. Since the torque due to gas pressure and that due to inertia are independent quantities, one varying with speed and the other with load, it is well to study them separately.[1, 2, 4] This paper is confined to a consideration of the torque due to gas pressure.

The torque from a single cylinder engine is conveniently expressed as a Fourier's series. The form is particularly convenient because of the ease with which torque from a number of cylinders may be added, as well as the ease of solution of the equation of the vibrating system when the forcing function is expressed as a sum of harmonic terms. Lewis[3] expressed the torque of large Diesel engines in this form. Muir and Terry[4] computed harmonic coefficients of gas pressure torque for an aircraft engine. These experimenters investigated the variation of the harmonic coefficients of the torque series with load. In obtaining coefficients, these investigators relied upon calculated indicator diagrams. The desire for more accurate results as well as for more complete information regarding the variation of the torque series with operating conditions led to the present investigation. The work was greatly facilitated by the M.I.T. Pressure Indicator with which torque could be investigated under conditions where attempts at calculation would have been worthless.

The method of obtaining the results herein presented was as follows: a series of indicator diagrams was taken on the N.A.C.A. Universal Engine under the conditions to be investigated. Fig. 1 is such a diagram. Torque was computed from the diagrams with the aid of the geometry of the mechanism. (Crank-connecting rod ratio .291.) A plot of torque against crank angle, Fig. 2, made to the proper scale, was run through a Coradi harmonic analyser and the coefficients determined. Fig. 3 shows the values of the coefficients of the harmonic series representing the torque as a function of crank angle which were obtained from the Coradi machine. The torque series may be represented as follows:

$$\frac{T}{T_m} = 1 + u_{\frac{1}{2}} \sin \tfrac{1}{2}\theta + u_1 \sin \theta + u_{1\frac{1}{2}} \sin 1\tfrac{1}{2}\theta + u_2 \ldots + v_{\frac{1}{2}} \cos \tfrac{1}{2}\theta + v_1 \cos \theta + v_{1\frac{1}{2}} \cos 1\tfrac{1}{2}\theta + \ldots$$

$$= 1 + \sum_{n=\frac{1}{2},\,1,\,1\frac{1}{2}\text{ etc.}}^{n=\infty} \left[ u_n \sin n\theta + v_n \cos n\theta \right]$$




Figs. 1 & 2

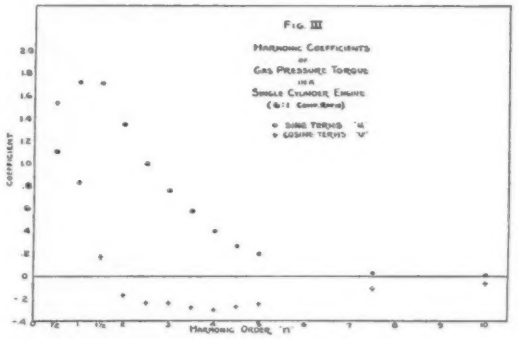



Fig. 3

[1] Tanaka, K., *Inertia Forces and Couples in the Radial Engine*, Report No. 10, Aeronautical Research Institute, Imperial University of Tokio, 1925.

[2] Root, R. E., *Dynamics of Engine and Shaft*, John Wiley, 1932.

[3] Lewis, F. M., *Torsional Vibration in the Diesel Engine*, Transactions of the Society of Naval Architecture & Marine Engineering, No. 33, 1925.

[4] Muir and Terry, *Harmonic Analysis of the Torque Curves of a Single Cylinder Engine*, Gt. Britain Aero. Research Committee R & M No. 1305, 1930.

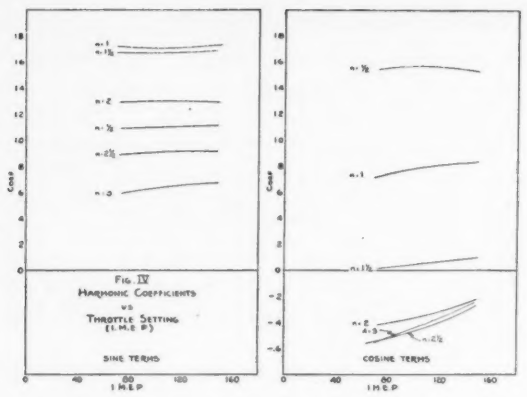



FIG. 4

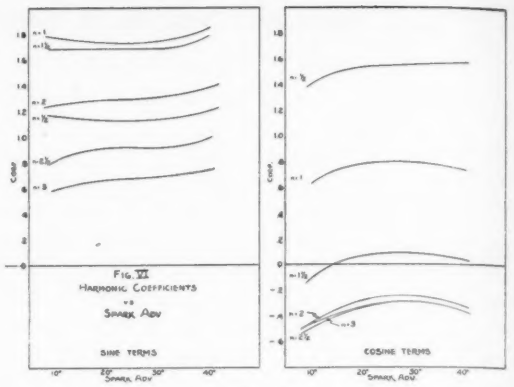



FIG. 6

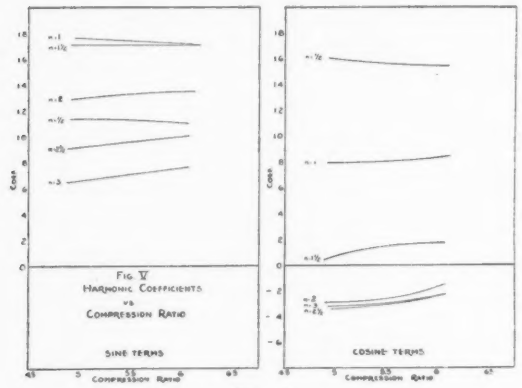



FIG. 5

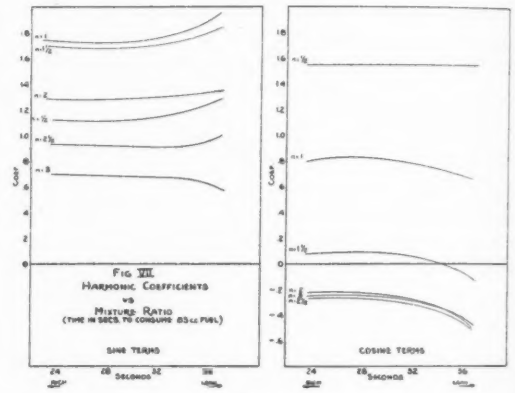



FIG. 7

where $T$ is the instantaneous torque, $T_m$ is the mean torque, $\theta$ the crank angle, $u_n$ and $v_n$ the harmonic coefficients, and $n$ the harmonic order. The fractional values of $n$ indicate merely that the torque from one cylinder is periodic with two revolutions.

A series of determinations was made for conditions of varying throttle, compression ratio, spark advance and mixture and the resulting harmonic coefficients up to $n = 3$ have been plotted in Figs. 4, 5, 6 and 7. From observing these plots, it will appear that operating conditions have little effect on the value of the coefficients and that when a change in engine conditions changes the value of $u$, it often has an opposite effect on the value of $v$; and we are led to the conclusion that the absolute magnitude of any harmonic coefficient, $w^2 = u^2 + v^2$ may remain even more nearly constant while the phase angle, $\phi = \tan^{-1} \frac{u}{v}$ may be the quantity that varies as operating conditions are changed. In order to study this, the series may be written

$$\frac{T}{T_m} = 1 + \sum_{n=\frac{1}{2},\,1,\,1\frac{1}{2},\,\text{etc.}}^{n=\infty} w_n \sin(n\theta - \phi_n)$$

where $w^2 = u^2 + v^2$ and $\tan \phi = u/v$.

Up to $n = 3$ the individual values of $u$ and $v$ are of interest since the inertia torque has an appreciable third order term. Addition of inertia and gas torque requires that we know the phase. When $n > 3$, however, the inertia torque is negligible, the phase angle is of little interest and the magnitude of $w$ gives all the desired information.

Fig. 8 is a plot of $w$ against $n$ for all of the observed data. Confirming our guess, the values of $w$ are seen to change very little with engine conditions and the data for these points is well represented by the relation $w = 8.02/n.^{2.16}$ If $w$ were inversely proportional to $n^2$, it would indicate that the torque-crank angle relation had discontinuous slope. Since we know that engine torque varies smoothly the power of $n$ must actually be somewhat greater than 2. For the highest compression ratio used (6 to 1) we know that the torque-crank angle curve is more nearly discontinuous in slope and we find that the points are better represented by the relation $w = 7.7/n^2$. The advanced spark runs show a similar characteristic. In the case of very lean mixtures, the exponent of $n$ is greater than 2.16.

This is because of the slow burning which accompanies lean mixtures and gives a smoother torque curve.

An interesting conclusion from this work is that the torsional "roughness" of a normal engine, which may be defined as $(T_{max} - T_{min})/T_{mean}$, will be approximately inversely proportional to the square of the number of cylinders (for more than six cylinders).

Along these lines the following fields remain to be investigated: (1) the effect of a change in crank to connecting rod ratio on the harmonic coefficients of torque; (2) the effect of the articulated connecting rod construction; and (3) the variation of friction torque with crank angle.

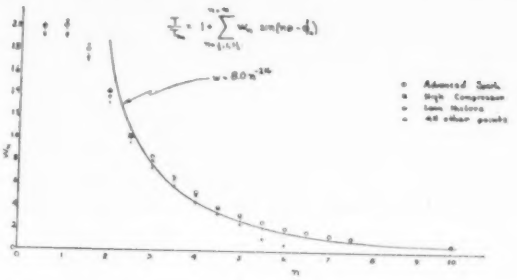


FIG. 8

# The Design of Ports and Valves for Aircraft Engines

*Presented at the Engines and Propellers Session, Fourth Annual Meeting, I. Ae. S.*

C. F. TAYLOR, *Massachusetts Institute of Technology*

Excluding mechanical problems, the factors of practical importance with regard to the internal combustion engine can be classified under either one of two headings, namely, capacity and efficiency. Of major importance in controlling capacity are those factors which govern the flow of gases into and out of engine cylinders, and of these, the shape and size of the valve and valve ports are of especial interest.

## PREVIOUS WORK

A considerable number of data are available concerning the flow coefficients of poppet valves, [1, 2, 3, 4, 5, 6] but a review of the literature reveals very little information on the influence of the valve ports immediately adjacent to the valves. There is even less information available on the effect of valve size, and of valve and port design, on actual engine performance. In view of the need of information in these fields, a program of study of port design and of the effect of valve and port design on engine performance, has been inaugurated at the Massachusetts Institute of Technology. The first two investigations made under this program have yielded interesting results, and are the subject of this paper.

## PORT DESIGN

An investigation, carried out by S. W. Doroff and K. F. Ryder in the spring of 1934, was directed specifically to a determination of the possibilities of reducing the size of ports below that customarily used on radial air-cooled aircraft engines. This possibility is of practical interest in that any reduction in port area can usually be reflected in a reduction in engine diameter.

In the typical inlet port (Fig. 1), the cross-sectional area of the port is made nearly equal to the area of valve opening at maximum lift. When this is the case, it is obvious that the chief restriction to flow is the valve, rather than the port, even when the valve is at maximum lift. Since the valve is at maximum lift only a small fraction of the time, the restriction caused by the port will be even less under actual operating conditions. In view of these facts, it seemed possible that a considerable reduction in port area, below usual practice, could be made without serious decrease in the orifice coefficient of the valve and port together. These tests were made to determine the effect of such reduction.

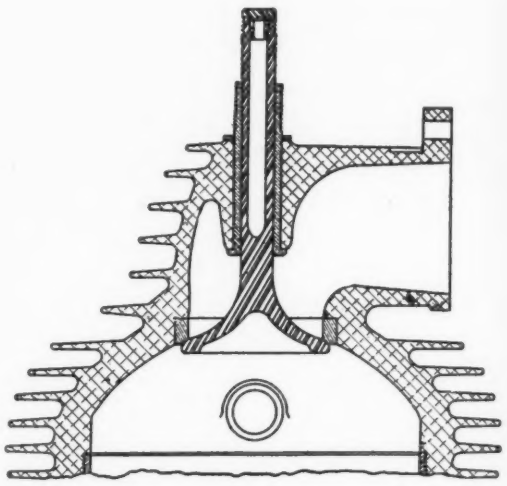


FIG. 1. Inlet Port.

## APPARATUS

The Pratt & Whitney Hornet "B" cylinder used is shown in Figs. 7 and 8 and pertinent dimensions are given in Table I. Air was drawn through a system consisting of an air meter, the cylinder, and a control valve, by means of a centrifugal blower. The mouth of the cylinder was sealed, the air from the metering tank entering the inlet port, passing into the cylinder, and leaving the exhaust port, which was connected to the pump suction line. Alcohol manometers were used to measure the static pressure drop from inlet line to cylinder, and from cylinder to exhaust line. Inlet and exhaust ports were tested separately, the valve being removed from the one not under test.

[1] Nutting & Lewis, *Air Flow Through Poppet Valves*, N.A.C.A. Technical Report No. 24, 1918.

[2] Eck, *Potential Flow in Engine Valves*, N.A.C.A. Technical Memorandum No. 343, 1925.

[3] Tanaka, *A Study of the Potential Flow of Gas Through the Poppet Valve*, Society Mechanical Engineers (Japan), July, 1926.

[4] Tanaka, *Air Flow Through a Suction Valve of Conical Seat*, Report of the Aeronautical Research Institute, Tokio Imperial University, Part I, No. 50, October, 1929. Part II, No. 51, November, 1929.

[5] Tanaka, *Air Flow Through Exhaust Valve of Conical Seat*, Report of the Aeronautical Research Institute, Tokio Imperial University No. 67, January, 1931.

[6] Dennison, Kuchler & Smith, *Experiments on the Flow of Air Through Engine Valves*, Transactions of the A.S.M.E. Oil and Gas Power Division, 53-6, 1931.

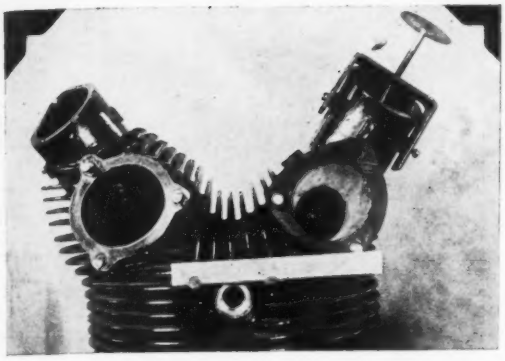


FIG. 2. Exhaust Port with maximum restriction. (Run 13).

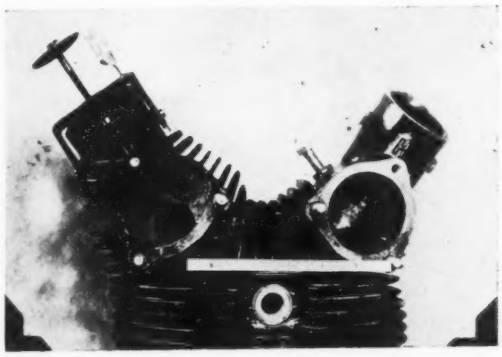


FIG. 3. Inlet Port with maximum restriction. (Run 5).

FIG. 4. Port sections at Flange.

FIG. 5. Port sections between Flange and Valve.

FIG. 6. Port sections near Valve.

## PROCEDURE

Each port was progressively made smaller by the use of plasticene, which was inserted in such a way as to "streamline" the flow as well as possible. With each arrangement of the plasticene, runs were made at various positions of the valve from maximum lift down to very small lift. Data from these runs were reduced to terms of the orifice coefficient of the port and valve assembly. The valve lifts are given in terms of the ratio L/D, lift to clear diameter.

The way in which the plasticene was used is illustrated in Figs. 2–6 inclusive. Plaster casts of the ports were made, sectioned, and the outline of the plasticene marked on the sections, as shown in Figs. 2, 3 and 4. Each arrangement of the plasticene is identified by a run number and by the ratio of port area at the flange to that of the unmodified port. It will be noted that in every case the plasticene was inserted so as to reduce the height of the port as much as possible, at the same time retaining an approximately circular cross-section.

## RESULTS

The results for the exhaust port are shown in Fig. 7, and those for the inlet port in Fig. 8. In order to make the results of general application, it is convenient to make use of the ratio: R = port area/valve opening area, the denominator term being taken at a valve lift equal to ¼ of the clear valve diameter (L/D = ¼). Table I gives this ratio for the various runs.

For the exhaust port, it will be noted that a reduction in port area of 31.3 percent, from R = .945 to R = .65, had very small effect at low lifts, and reduced the coefficient only 7 percent at maximum lift. The results of the exhaust valve test reported in the second part of this paper indicate that very considerable restrictions in exhaust-valve-opening area can be made without adversely affecting engine output. From this it seems safe to conclude that the exhaust port areas could also be cut down considerably without reducing output.

The inlet port has a lower ratio of port area/valve area (R = .91) to start with, and it would be expected that a reduction of similar magnitude would have a greater effect on flow. That this is true, is shown by test No. 7 (Fig. 8) where the reduction in coefficient due to a 38 percent reduction in R is found to be 20 percent at L/D = .25. The effect on engine output would be somewhat less than this, however, for the valve is near maximum lift only a small portion of the time. With the usual cam contour, the average lift of

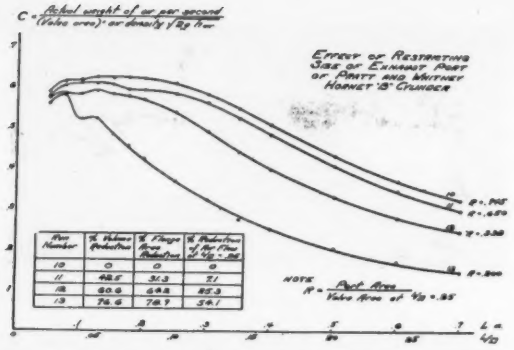



FIG. 7. Effect of Exhaust Port restriction on flow coefficient at various valve lifts.

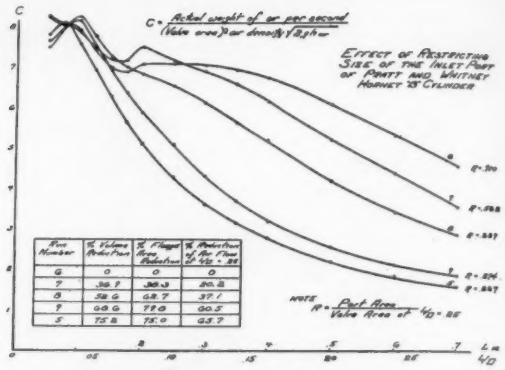



FIG. 8. Effect of Inlet Port restrictions on flow coefficient at various valve lifts.

the valve during its open period corresponds to an L/D of about .18, at which figure the reduction in coefficient is 14 percent. But it will be noted that in this case the ratio of port area to valve area is only .562. In practice, a somewhat larger ratio should be used, as a 14 percent sacrifice in volumetric capacity is not desirable.

A serious limitation on these tests was the fact that the shape of the ports was restricted by the particular design used as a base for the experiments. It is probable that a more effective shape for the ports could be found for each cross-sectional area, and this might alter the character of the results. Investigations to determine the optimum shape of valve ports, within the limitations imposed by valves, manifolds and cooling, might be very profitable.

## Exhaust Valve Tests

The research on exhaust valve size was carried out by J. H. Hrones and W. S. Kut who investigated the possibilities of reducing exhaust-valve areas below those normally used.

Fig. 9 is a typical light-spring indicator diagram from an unsupercharged engine with exhaust-valve area equal to inlet-valve area. It is quite apparent that the major part of the pumping loss is due to the difference between inlet pressure and atmospheric pressure, very

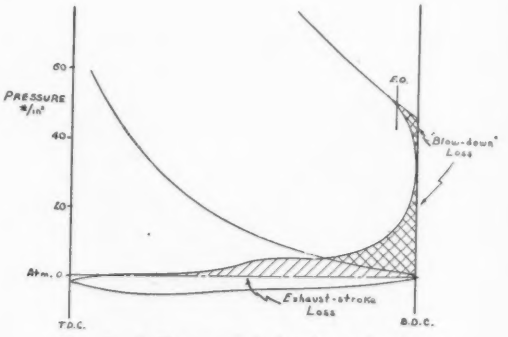



FIG. 9. Indicator card showing valve losses

little being due to the positive pressure required to force out the exhaust. This is because of the very low density of the exhaust gases, and also because of the favorable effect of the inertia of the outgoing gases.

The chief loss in work due to the exhaust process is indicated by the cross hatched areas in the figure, and these occur during what we may call the "blow-down" period, or the time between the beginning of exhaust-valve opening and the attainment of the normal exhaust-stroke pressure. Consideration of such light-spring diagrams immediately suggests the possibility of decreasing the exhaust-valve sizes without serious

TABLE I

Pratt & Whitney Hornet "B" Cylinder
Bore 6⅛" Stroke 6⅜"

| | Valve diam., in. | Opening area at L/D = .25 sq. in. | Port area at flange, no plasticene | $R = \frac{\text{port area,}}{\text{valve area}}$ at L/D = .25 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Run 5 | Run 6, no plasticene | Run 7 | Run 8 | Run 9 | Run 10, no plasticene | Run 11 | Run 12 | Run 13 |
| Inlet | 2.625 | 5.4 | 4.91 | .227 | .91 | .562 | .339 | .274 | ..... | ..... | ..... | ..... |
| Exhaust | 2.5 | 4.91 | 4.64 | ..... | ..... | ..... | ..... | ..... | .945 | .65 | .338 | .20 |

TABLE II

Results of Exhaust-Valve Tests. N.A.C.A. Engine, 5″ bore x 7″ stroke. *N.A.C.A. Head.* Four Valves, 2¼″ clear diameter each. Inlet Valve: lift 0.3 in., opens 15° B.T.C., closes 40° A.T.C.

| Run No. | Exhaust Valve | | | | R.P.M. | B.M.E.P. lb./in.² | B.H.P. |
|---|---|---|---|---|---|---|---|
| | opens B.B.C. | closes A.T.C. | Lift in | Ratio lift/dia. | | | |
| 1 | 65 | 35 | .425 | .189 | 700 | 117.0 | 14.2 |
| | 65 | 35 | .225 | .100 | 700 | 117.7 | 14.3 |
| 2 | 55 | 35 | .425 | .189 | 700 | 119.4 | 14.5 |
| | 55 | 35 | .225 | .100 | 700 | 121.0 | 14.7 |
| 3 | 50 | 35 | .425 | .189 | 700 | 121.0 | 14.7 |
| | 50 | 35 | .225 | .100 | 700 | 122.0 | 14.8 |
| 4 | 40 | 35 | .425 | .189 | 700 | 122.7 | 14.9 |
| | 40 | 35 | .225 | .100 | 700 | 122.7 | 14.9 |
| 5 | 35 | 35 | .425 | .189 | 700 | 123.7 | 15.06 |
| | 35 | 35 | .225 | .100 | 700 | 122.7 | 14.9 |
| 6 | 65 | 35 | .425 | .189 | 1200 | 130.7 | 27.2 |
| | 65 | 35 | .225 | .100 | 1200 | 134.7 | 28.0 |
| 7 | 50 | 35 | .425 | .189 | 1200 | 138.0 | 28.7 |
| | 50 | 35 | .225 | .100 | 1200 | 138.8 | 28.9 |
| 8 | 40 | 35 | .425 | .189 | 1200 | 140.0 | 29.1 |
| | 40 | 35 | .225 | .100 | 1200 | 141.2 | 29.4 |
| 9 | 35 | 35 | .425 | .189 | 1200 | 141.2 | 29.4 |
| | 35 | 35 | .225 | .100 | 1200 | 141.0 | 29.3 |
| 10 | 65 | 35 | .378 | .167 | 1800 | 126.2 | 40.2 |
| | 65 | 35 | .225 | .100 | 1800 | 125.0 | 39.7 |
| 11 | 55 | 35 | .378 | .167 | 1800 | 126.0 | 40.0 |
| | 55 | 35 | .225 | .100 | 1800 | 124.2 | 39.5 |
| 12 | 50 | 35 | .378 | .167 | 1800 | 122.8 | 39.0 |
| | 50 | 35 | .225 | .100 | 1800 | 122.1 | 38.8 |
| 13 | 40 | 35 | .378 | .167 | 1800 | 119.6 | 38.0 |
| | 40 | 35 | .225 | .100 | 1800 | 119.2 | 37.9 |
| 14 | 35 | 35 | .378 | .167 | 1800 | 118.2 | 37.6 |
| | 35 | 35 | .225 | .100 | 1800 | 118.2 | 37.6 |
| *M.I.T. Head.* | Four valves, 1⅝″ dia., 7/16″ lift, I.O. 50° B.T.C., I.C. 50° A.B.C. | | | | | | |
| 15 | 60 | 50 | 2 exhaust valves | | 700 | 119.5 | 14.5 |
| | 60 | 50 | 1 " " | | 700 | 112.9 | 13.7 |
| 16 | 60 | 50 | 2 " " | | 1200 | 132.0 | 27.5 |
| | 60 | 50 | 1 " " | | 1200 | 133.5 | 27.8 |
| 17 | 60 | 50 | 2 " " | | 1800 | 121.1 | 38.5 |
| | 60 | 50 | 1 " " | | 1800 | 122.1 | 38.8 |

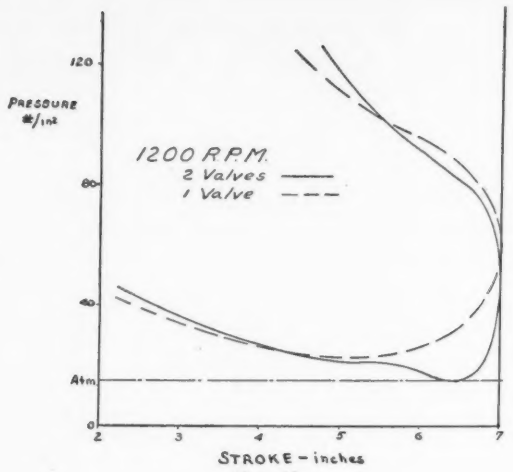


FIG. 10

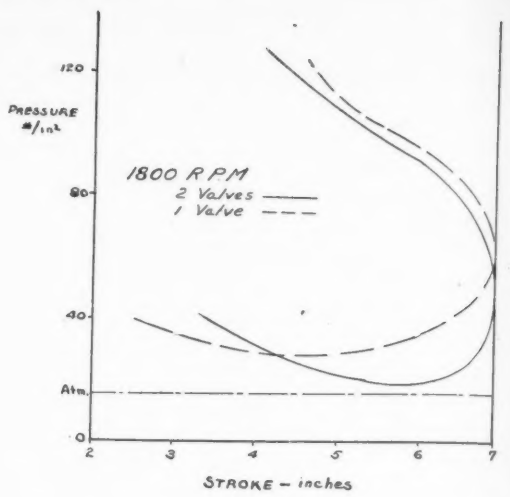


FIG. 11

increase in pumping loss, thus making room for an increase in inlet-valve size which might not only reduce the net pumping loss, but would tend to improve volumetric efficiency and output.

An N.A.C.A. Universal Test Engine [7] was used. This has a 5" x 7" cylinder with two inlet and two exhaust valves, each of 2¼ inches clear diameter. A mechanism is provided for varying the valve lift during operation. An electric cradle dynamometer was used to measure output. Indicator diagrams were made with the M.I.T. Indicator.[8]

Engine performance was measured with normal inlet-valve lift, and with various exhaust-valve lifts, with both exhaust valves in operation. Runs were made at speeds of 700, 1200 and 1800 r.p.m., and with exhaust-valve-opening time varying from 65 to 35 degrees before top center, the closing being at 35 degrees A.T.C. in all cases. Supplementary runs were made with a cylinder head having four 1⅝ inch valves lifted 7/16 inch, with two exhaust valves and with but one exhaust valve in operation. Inlet conditions, fuel-air ratio, etc. were held constant in all tests, the variables of chief interest being the output and the indicator diagrams.

Table II summarizes the results of these tests. With the 2¼ inch valves no appreciable reduction in power was observed when the exhaust valve lift was decreased from .425 inch (.19 x diameter) to .225 inch (.10 x diameter), the minimum lift allowed by the valve gear. While the indicator diagrams plotted on a pressure-time basis showed an appreciable increase in cylinder pressure during the "blow-down" period as the lift is decreased, on a pressure-volume basis the change in diagram area was insignificant.

With the 1⅝ inch valves, the use of one exhaust valve in place of two gave an appreciably greater loss in diagram area during the "blow-down" period (Figs. 10 and 11). At 700 r.p.m. this caused an appreciable loss in brake output, but at 1200 and 1800 r.p.m. there was actually an increase in brake output when one exhaust valve was taken out of operation. This appears to have been due to an increase in volumetric efficiency, since the expansion curves are definitely higher with one valve than with two. Evidently the smaller exhaust-valve opening resulted in an inertia effect, at the two higher speeds, which lowered the pressure of the residual gases at the start of the inlet stroke. The spring scale used, however, was too great to show this on the diagrams.

The amount of reduction in exhaust-valve area possible without serious effect on engine power is remarkable. This indicates the possibility of improving the performance of unsupercharged engines considerably by reducing exhaust-valve size, and taking advantage of the space thus made available to increase inlet-valve size. There is also evidence to show that, even when inlet-valve size is held constant, the optimum exhaust-valve size, from the point of view of maximum output, may be considerably smaller than present practice dictates. Since, however, the possible direct improvement due to restricting the exhaust-valve size depends on a dynamic effect, the optimum exhaust-valve size will vary with speed, and with the design of the exhaust piping. Further research on this point would be desirable.

In the case of supercharged engines, the optimum ratio of exhaust-valve area to inlet-valve area will probably increase with increasing supercharging pressure. As this pressure increases, the increasing pressure-difference available across the inlet-valve makes the need for large inlet-valve area less urgent. On the other hand, the increasing cylinder pressure at exhaust-valve opening will make "blow-down" losses more important. Extension of the investigation into the range of the supercharged engine is planned.

[7] Ware, *Description of N.A.C.A. Universal Test Engine and Some Test Results*, N.A.C.A. Technical Report No. 250, 1927.

[8] Taylor & Draper, *A New High Speed Engine Indicator*, Mechanical Engineering, March, 1933.

# A Survey of Engine Development

*Presented at the Survey of Engine Development Session, Fourth Annual Meeting, I. Ae. S.*

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For the purpose of discussion and analysis engine types may be classified as being used for airplanes for military, transport and private flying.

## MILITARY AND TRANSPORT ENGINES

There is a definite trend in both military and transport engines toward higher power and lower fuel consumption. The engine for the private airplane is predominated by the single-row aircooled radial with a tendency toward the use of supercharger engines.

## COMPARISON OF ENGINE TYPES

Without question the air-cooled radial type predominates in general thruout the world although in England, France, Germany and Italy liquid-cooled engines are in competitive production with air-cooled engines. A certain amount of development work on liquid-cooled engines is still in progress in this country by four of the aircraft engine builders but only one liquid-cooled engine remains in limited production for military purposes. Whether the trend of the times has made this country close its eyes to this development is still a debatable question. Can the liquid-cooled engine overcome its handicap of about ⅓ lb. per hp.? Apparently some designers believe so as indicated by a recent low wing monoplane pursuit developed in England. This ship is reported in the current periodicals to develop a speed of 300 m.p.h. No figures on horsepower and altitude rating are given but judging from observation of past performances the writer would venture the guess that the altitude was at least 15,000 ft. and the power at least in four figures. The engine no doubt for take-off and short period operation is overspeeded about 15% as is usual English practice. No difficulty should be experienced in equalling this performance with air-cooled engines providing they are cooled adequately at high altitudes which is being accomplished.

With the present mean effective pressures of 175 to 200 lbs. per sq. in. the air-cooled engine appears to cool with sea level power at any altitude which is useful tactically. Proponents of liquid-cooled engines will state that higher mean effective pressures are available with liquid-cooled engines which may be true academically but not from a practical standpoint. Other factors than cylinder cooling limit all engines from exceeding present cylinder pressures. Piston cooling is one of the important difficulties. Spark plugs which are cool enough for high power are too cool for lower power running. The difficulty of controlling oil consumption at high engine speed in large bore cylinders is a limiting factor. Small bore multi-cylinder engines to get large displacement are not desirable on account of their high specific weight.

## TREND OF ENGINE TYPES

In this country there is a decided trend toward double-row radial engines. There is only one excuse for a two-row engine in place of a single-row engine in powers which can be handled satisfactorily by the latter. This excuse is the small diameter which is useful in single engined military airplanes where good vision past the engine is necessary.

The simplicity, accessibility, lower first cost, lower maintenance cost and reliability features of the single-row radial engine are strong arguments in its favor. Where the power per cylinder becomes too great for the single-row engine then the double-row engine is necessary except for the one reason given above. The fuel economy of the single-row engine is as good if not better than the double-row engine since the latter has a slight handicap in its more difficult gas distribution problem. Laboratory and flight tests indicate little difference in fuel economy between the two types. Actual laboratory tests on the single-row engine at cruising power with high octane number fuel have given consumption figures below .35 lbs.-b.hp.-hr.

## DYNAMIC DAMPER

The introduction of the dynamic damper as applied to the crankshaft system of the radial engine has removed one of the most difficult problems from this type of engine, namely, the periodic torsional vibrations. This development represents without question one of the most valuable contributions to aircraft engine design in many years.

## ENGINE SPEED

Normal engine speeds have increased very slightly during the past ten or twelve years and except for take-off and emergency operation a radical increase in engine speed cannot be expected. There may be a gradual increase in engine speed.

Considerable advantage in power at altitude for

military purposes can be gained by increasing engine speed and consequently displacement per minute. In payment for this increase in engine speed there can be expected an increase in oil consumption, gas consumption and specific weight of the power plant if the same reliability is to be maintained. However, the power advantage can be realized by restricting the use of the high speed and power for short periods without sacrince and with a decrease in specific weight.

### Engine Ratings

The trend in this case leads toward a wider difference between cruising and maximum power. The cruising power of an engine actually should be considered its rated power. The present rating should be called its homologation or type test rating, and the overpower should be classified as an emergency and take-off rating. The English have used this method of rating for some time, and while originally developed to permit fixed pitch propellers to turn at rated speed to assist take-off, they are retaining the ratings and consequently the increased performance with controllable propellers.

### Cruising Speed

Low engine speed for cruising is of course desirable from the standpoint of stresses which increase as the square of the speed. Oil consumption is proportional to speed and low cruising speed is to be preferred. With low engine speed less power is consumed by engine friction which is reflected in lower specific fuel consumption. Less supercharger pressure is required to maintain a given manifold pressure at low engine speed which is another point in favor of low engine speed for cruising.

### Engine Weight

The demand from commercial operators for further increases in durability from their engines can be answered by operating large displacement engines at a low percentage of maximum power rating. This system is better than attempting to put additional weight into some of the major parts of the engine.

An engine can be operated at take-off power on high octane fuel and cruised on 80 octane fuel at 40 to 50% of the take-off power and at somewhat lower than the take-off crankshaft speed. Intermediate ratings for cruising and level flight can be used for military purposes. The same engine can therefore serve both purposes which is necessary until such time as the commercial business can support the development of special engines. The need for special engines for commercial transport operation is very doubtful except for the possible arrangement of accessories which will also be useful in bombardment airplanes. Reference is made to driving all accessories thru a remote drive or separate power unit.

Increase in weight alone will not necessarily prolong the life of an engine. Valves which have their life affected by lead content in the fuel would not be improved by additional weight. Valve gear, pistons, piston rings, crankshafts and many similar parts would not be improved by adding weight. Additional bearing area on heavily loaded bearings would prolong bearing life, but the loss of payload involved in such a major change plus the decrease in market caused by such a change would be unwarranted.

No engine has a perfectly balanced design which could not have weight added or subtracted from some parts. Actually an engine becomes obsolescent when it reaches this stage of refinement.

It is unfortunate that when an airplane is designed that almost invariably the engine has become too low in power by the time the ship is in production. Again the answer lies in more conservative cruising speed guarantees by the airplane designer, a disregard of the airplane speed at full throttle at critical altitude at normal rated engine speed which is never needed, and more attention to the use of high power for take-off with better fuel.

No airplane designer desires additional weight in the power plant as his task of maintaining high airplane speed at cruising and still landing the airplane within requirements is not small. Experience has proven that low specific weight is absolutely necessary, and that the airplane designer and operator will not give countenance to the addition of weight in the final analysis.

### Automatic Devices

With the introduction of supercharged engines and controllable pitch propellers the need for relieving the pilot of the manual operation of many controls is quickly seen by taking one look at the instrument board of a modern military or transport airplane. Any engine which cannot be operated at full throttle at sea level should be equipped with an automatic manifold pressure control which will limit the pressure to the maximum permissible. The next most necessary control in the interests of safety is one which will control the temperature of the air entering the supercharger. Such a control is under development but not yet available. Many engine difficulties are caused by detonation aggravated by the use of excessive carburetor intake air heat. At present this most important control must be operated manually and has to date been the source of considerable trouble primarily thru a lack of knowledge and experience to permit the pilots to use the control properly.

Automatic oil temperature regulators are necessary and are in regular use.

Automatic mixture controls are necessary particularly with the introduction of the constant speed propeller. Even without the constant speed propeller 10 to 15%

saving in fuel can be expected when using the automatic mixture control. One semi-automatic device which controls the mixture up to critical altitude providing that constant air intake temperature is used is in service giving satisfactory results. Another device which is sensitive to both altitude pressure and temperature but which must be manually set to control fuel-air ratio automatically for take-off, level flight and cruising will be available soon. The fully automatic device to provide a change in specific fuel consumption with a change in manifold pressure is not yet available but will be a welcome addition to the increasing family of automatic devices.

### Fuel Economy

Considerable progress has been made during the past year on the reduction of fuel consumption of engines in the laboratory and in flight. Using present engines and fuels, transport operators can expect about 10% saving in fuel by getting better control of the carburetor fuel-air ratio. Indicators are available which enable the pilot to set the control accurately and should be used as a visible check on the operation of any automatic device particularly on long flights or where the gasoline supply is limited. Such devices will pay for themselves in a very short time.

### High Octane Number Fuels

One of the most valuable contributions to the progress of aviation in recent years is the development of fuels of octane number greater than 87 (CFR Motor Method) without the use of excessive quantities of tetraethyl lead. The possibility of using this fuel without lead at an octane number of 80 (CFR Motor Method) at cruising outputs has not been fully appreciated as yet by the operators of transport airplanes.

It is believed that the reduction in difficulties directly traceable to the use of lead would more than offset the slight increase in cost which is inevitable when introducing a new product. Particular emphasis should be placed on the increase in reliability which means elimination of trip cancellations and an increased confidence in the equipment by the public. Leaded fuels for take-off are necessary and desirable for maximum performance. They are necessary for military engines.

The use of fuels of 90 to 100 octane (CFR motor Method) number for take-off and climb even in present engines offers several advantages:

(1) Additional power at sea level from a supercharged engine without the danger of encountering detonation. Therefore in emergency the factor of safety is much greater since the effect of detonation on take-off is very serious resulting in complete loss in power if the detonation is of sufficient severity.

(2) Some improvement in fuel consumption at cruising is possible with the higher octane fuels, since it is possible to lean out the mixture further before detonation becomes the limiting factor.

Little gain from the use of high octane fuel can be expected from an engine which can be operated at sea level at full throttle, but the use of such engines has been practically discontinued in transport or bombardment airplanes today.

By changes in the engines such as higher cylinder compression ratios to take further advantage of the higher octane fuels a material saving in fuel probably 10% will result. Such changes could be made in existing equipment during overhaul providing proper operating instructions were issued and followed upon resumption in service by the engine.

The introduction of these new fuels is passing thru the same cycle as experienced when 73, 80 and 87 octane number fuels were placed on the market. The result is inevitable particularly from a military standpoint as the strength of an air force is increased tremendously by an improvement change in fuel. The increase in payload and the decrease in troubles and final cost should mean something to the commercial operator.

Great concern at the high specific fuel consumption of engines during high power operation for take-off is sometimes felt by the airplane designers and operators but such operation is for limited periods only, and these same engines either liquid or air-cooled which can now cruise between .45 and .50 lbs. per b.hp.-hr. will be able with the better fuels and improved design to operate at cruising powers as low as .40 lbs. per b.hp.-hr.

The outstanding developments and trends in aircraft engines during the past year are:

1. Introduction of the dynamic damper.
2. Trend toward double-row radial air-cooled engines.
3. Continued development of liquid-cooled engines.
4. Development of automatic control devices.
5. Increased development of higher octane number fuels.
6. Decrease in fuel consumption of aircraft engines.
7. Continued predominance of single-row radial air-cooled engine in the field below 1000 hp.

## Discussion on "A Survey of Engine Development"

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Mr. Nutt has given a very able and interesting paper on this subject. However, he has not covered one possibility which seems to me distinctly interesting at the present time.

With the advent of the modern "clean" airplane with no external bracing and with retractible landing gear, the drag of air-cooled radial engines is likely to be from 20 to 30 percent of the total drag of the airplane in the high-speed condition. This is in spite of the use of the very best forms of cowling and the best engine and propeller position with reference to the wing, as determined by the work of the N.A.C.A. A consideration of these facts makes it of interest to consider the possibility of engines enclosed entirely within the wing structure.

With the wing sizes now in vogue in multi-engined airplanes, it is obvious that the "enclosed" engine could not be of radial or Vee form. With a tractor propeller, the engine would normally be located near the thickest section of the wing and it might be possible to use a "flat X" cylinder arrangement. For pusher installations, however, the horizontal-opposed type seems preferable in order to minimize propeller-shaft length. This type could be made relatively "thin" at the rear, where it is housed near the trailing edge, and the accessories could be located forward where a greater wing thickness is available.

The development of satisfactory enclosed power plants will depend not only on the development of satisfactory engines of proper form, but also on the satisfactory solution of the problems of cooling, mounting structure, accessibility, etc. Of these, cooling is probably the most difficult. If the engine is to be air-cooled, there is the problem of drawing in the air and discharging it where it will give minimum interference with wing and propeller performance. Tests made at M.I.T. some years ago indicate that if circulation is obtained by virtue of the pressure differences existing between different parts of the wing surface, a prohibitive amount of drag would be involved. If air cooling is to be accomplished by utilizing airplane and slipstream velocities, the present radial engine with N.A.C.A. cowling probably involves as small an amount of over-all drag as any feasible arrangement. It seems probable, therefore, that an enclosed air-cooled engine would require some sort of blower system. Such systems absorb a considerable portion of the engine power, and the net result might easily be poorer engine performance with respect to weight and drag than could be obtained by a suitable liquid-cooling system.

Experience with liquid-cooling indicates that if the ordinary core type radiators are used, the gain to be expected from the completely housed engine would be largely offset by the weight and drag of the cooling system. The wing-skin radiator, until recently at least, has been regarded unfavorably on account of its weight and because of the technical difficulties involved in securing good cooling performance. This general antipathy to wing-skin radiators, however, seems to be a carry-over from the days when they were applied to fabric or plywood-covered wings. In such cases, the skin type radiator was a heavy and cumbersome addition, without structural function. Unfortunate British experience with wing-skin radiators and steam cooling has also been cited against this type, but the troubles seem to have been inherent in the steam cooling rather than in the type of radiator used. Now that most wings are covered with metal, it would seem logical to reconsider the wing-skin type of radiator with a view to utilizing the existing wing surfaces. If this be possible, and I see no reason why it should not, liquid-cooling for the enclosed engine begins to look very attractive. It appears that, in the average design, enough cooling surface for cruising can be obtained by utilizing the leading edge only, and it might be possible to spray cooling liquid against the inside surface of the leading edge with a simple system of pipes and spray orifices, and a sump to collect the cooling liquid which would drain back to the center section with suitable dihedral in the wings. In many cases retractible auxiliary radiators would be necessary for take-off and climb.

From past experience it appears that the liquid-cooled engine can be designed for about the same weight as the air-cooled engine. Assuming this to be the case, possible power reductions from the use of completely enclosed engines run up to 30 percent, if no additional weight and drag due to the cooling system is assumed. Very generous assumptions for the weight of cooling system, including retractible auxiliary radiators and sufficient additional wing surface to maintain the same wing loading, indicate a possible reduction of 15 percent in the power required for a given performance, as compared with an installation using modern radial engines. It appears that such gains cannot long be ignored, and that such research and development work as is now in progress on totally enclosed liquid-cooled engines may eventually have a very interesting application.

**PHILIP B. TAYLOR**
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The upward horsepower trend of the past fifteen years is continuing with a considerable degree of acceleration. It appears that the increasing popularity of four-engine planes will permit doubling the present airplane size with present powerplants, but the rapidity of increase in airplane size is already demanding larger powerplants even in the four-engine plane. The feeder line ship and carrier based Navy planes may not follow the trend for increased power immediately.

The form of engine becomes of less importance as the size of the airplane increases, because the engine will be masked by a thick wing and because the percentage of drag of the powerplants becomes smaller in large ships. This consideration and the fact that the engine weight in large ships is also of decreasing importance, opens the field for all types of engines with reliability, low fuel consumption, and smoothness of operation as the prime factors of selection within a horsepower class.

The two-stroke cycle engine will be required to compete on fuel consumption (which may be possible with fuel injection) and will also be required to show an acceptable degree of flexibility and controllability if it is to gain any degree of recognition.

The Diesel cycle seems to fulfil the new requirements but the present four-stroke cycle is preparing to give stiff competition on fuel consumption and is probably well out ahead on weight per horsepower.

The gas turbine and the compound reciprocating and exhaust turbo engine seem to be quiet at present but may emerge at any time when they are able to compete on the basis outlined above.

The time-honored competition between water and air cooled engines is continuing with air cooling at present in the ascendency because this type has, under present operating condition, overcome its inferiority in fuel consumption.

The demand for comfort in all types of planes has already had its effect on aircraft engine smoothness, but further improvements will be demanded and attained.

Supercharging has now caught up with the limitations of passenger safety and comfort. However, persistent military

demands for higher operating altitudes point to greater supercharging altitudes and the use of pressure cabins in commercial transport may at any time intensify the demand. The exhaust turbo holds first place for critical altitudes above 15,000 feet, with the geared supercharger holding its monopoly for lower critical altitudes.

Fuel injection has not and will not prove a panacea, but it presents an attractive means of eliminating ice formation in carburetors. An automatic control of mixture ratio is essential for the practical application of fuel injection. Fuel injection will of course be required to compete with non-icing carburetors and other devices for accomplishing the same purpose.

The sleeve valve cylinder is again receiving a great deal of attention and presents interesting possibilities of greater induction efficiency. The poppet valve is of course well established and will be difficult to displace.

While the aircraft industry moves with astonishing speed toward the engine of tomorrow, it is unlikely that any radical type will displace the present conventional designs without a period of stabilization for the new-comer extending over at least four years from the date of successful flight tests. An "ear to the ground" to detect the little stranger in our midst should make a fairly accurate prediction of types for a four year period possible.

# Compromises in Propeller Design

*Presented at the Engines and Propellers Session, Fourth Annual Meeting, I. Ae. S.*

DAVID BIERMANN, *National Advisory Committee for Aeronautics*

By "compromise in propeller design" in the present discussion is meant the improvement in propulsive efficiency for the take-off and climb conditions at the expense of efficiency at high speed. This idea is not new. In fact, nearly all propellers have been designed with a certain amount of compromise since the first airplane flew. The system was not productive of any great amount of gain, however, until controlled propellers were introduced, for with fixed-pitch propellers the losses nearly offset the gains. With controllable propellers, on the other hand, it has been possible in some cases to increase the take-off thrust by over 40 percent by compromising.

In order to illustrate the operating characteristics of various compromise designs a chart of propulsive efficiency against air speed has been prepared for an airplane chosen as an example (Fig. 1). In this figure the solid curves are lines of constant pitch and are included only to show the actual operating pitch of the propellers represented by the dotted lines.

If a controllable propeller that will have its maximum efficiency at the high speed, 250 m.p.h., should be selected, it would represent the condition of no compromise and the propulsive efficiency would follow the dotted curve marked 0° pitch reduction at different air speeds.

If a propeller of 3° less pitch and consequently greater diameter is selected, it may be noted that the high-speed efficiency is slightly less but that the efficiency at the latter part of the take-off run and at the climbing speed is considerably higher. Still greater improvements may be made in the take-off efficiency with lower pitch, greater diameter propellers up to a limiting condition wherein the operating curve touches the envelope of the efficiency curves at the take-off speed. Of course the high-speed efficiency progressively decreases with each improvement in take-off efficiency, but in smaller proportion.

The question immediately arises as to how far compromises should be carried. As in most designs, each problem must be solved on its own merits for there are a number of factors that are not apparent in this figure. In the first place the amount of improvement possible at the take-off depends on the design pitch or more roughly on the high speed of the airplane; the higher the pitch or speed, the greater the possible improvement. This is brought out in the next figure wherein the changes in thrust power are plotted against the approximate high speed for different degrees of pitch reduction (Fig. 2).

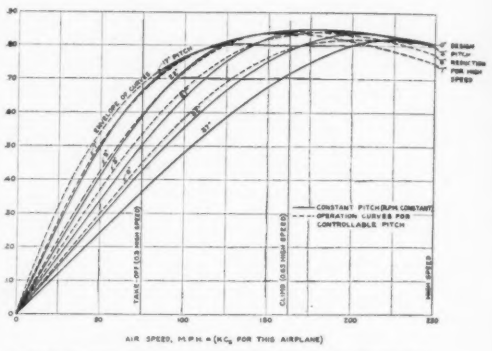


FIGURE 1 – OPERATION EFFICIENCY CURVES OF VARIOUS COMPROMISE CONTROLLABLE PROPELLERS FROM TAKE-OFF TO HIGH SPEED OF AN AIRPLANE CHOSEN AS AN EXAMPLE

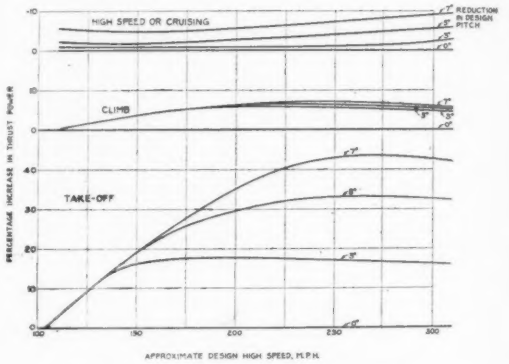


FIGURE 2 – EFFECT OF VARIOUS AMOUNTS OF COMPROMISE ON THE POWER AVAILABLE FOR VARIOUS CONDITIONS

In the lower part of the figure is the improvement in take-off thrust that may be obtained with different degrees of compromise. One may note that there is no advantage in compromising for airplanes in the 100 m.p.h. class, but as the design high speed increases the greater is the possible improvement.

In the central portion of the figure the improvement in climbing power is given. There is little gain by decreasing the design pitch below 3°.

At the top of the figure the loss in high speed and cruising power is given for different degrees of pitch reduction. These losses do not change much with changes in design speed.

These are other important factors affecting the degree of compromise desirable. In cases wherein propellers

NOTE: Data for figures were taken from N. A. C. A. propeller tests on a 4-foot model propeller mounted on a wing-nacelle set-up.

are designed for supercharged engines to operate at a certain altitude, at a certain engine speed, and at a certain value of engine power, but which are operated at take-off at a different altitude, at a different engine speed, and at a different value of engine power, these factors should be taken into account when determining the degree of compromise because each affect it.

It is readily seen that the pitch must be reduced when going from a region of rarified atmosphere at altitude into the denser atmosphere at sea level in order that the propeller absorb the same power—everything else remaining constant. This pitch reduction has the same effect on the take-off efficiency as does the same reduction made as a compromise but of course does not reduce the high-speed efficiency.

The pitch must be further reduced for any overspeeding of the engine at take-off.

Boosting the engine for take-off, however, has the opposite effect because the pitch must be increased to absorb the extra power.

The effect of each of these three factors on the equivalent compromise pitch reduction is shown in Fig. 3. On the left, lines of constant critical altitude are plotted with the ratio of sea level to critical altitude power as the abscissa, and on the right are plotted lines of constant pitch reduction with the ratio of sea level to critical altitude r. p. m. as the abscissa. The chart is read up from each side and across from side to side.

The chart shows that if there is no change in power or r. p. m. the altitude designs have the same effect on take-off as do compromise propellers. For example, it may be noted that for an airplane having a critical altitude of 10,000 feet (condition A) the pitch must be reduced 3½° for the same air speed at sea level, resulting in an increase of approximately 20 percent in take-off thrust for the high-speed airplanes. This pitch reducton results in the same improvement for take-off and climb as does a 3½° compromise propeller but does not affect the high speed or the cruising speed since these are measured at the critical altitude.

Since it is almost a universal practice to rate supercharged engines on different bases for different conditions of flight, the differences in engine power and engine speed obtained for take-off from that obtained for cruising or high speed must be taken into account when determining the amount of compromise desirable. At take-off the engine speed is generally increased as well as the manifold pressure. It is obvious that if the power is increased for the same air speed and engine speed, the pitch must be increased accordingly to absorb the extra power. This pitch increase has an effect on the take-off efficiency, the reverse of the effect of compromising so that even though the brake horsepower is increased the thrust horsepower will not increase in proportion because of the loss in propulsive efficiency. For example, if the power at constant r. p. m. or torque is increased by 10 percent (condition B), the pitch must

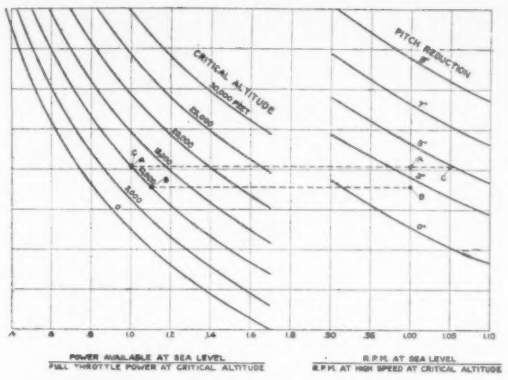


FIGURE 3.- A MEAN REDUCTION IN CRITICAL ALTITUDE HIGH SPEED PITCH MADE NECESSARY BY THE SEA LEVEL OPERATION OF SUPERCHARGED ENGINES

be increased by 1° (from A to B) with the result that the improvement in take-off efficiency will be reduced to approximately 14 percent. Since the engine power is increased 10 percent, the net increase in thrust power will be about 25 percent as compared to 32 percent had there been no loss in propulsive efficiency due to the added engine torque.

Consider the condition wherein the engine speed is increased and the engine power held constant (decreasing torque). For this condition the pitch must be reduced, resulting in improved take-off efficiency. For example, if the engine is overspeeded by 5 percent (condition C) the pitch must be reduced about 1½° (from A to C) or a total reduction of about 5° for the same speed, resulting in over 30 percent increase in take-off thrust power for high-speed airplanes as compared to 20 percent increase for the condition A.

It is quite evident, therefore, that if engine temperature, or power for a short time, is the limiting factor in rating engines for take-off, it is better to obtain that power at the highest possible engine speed rather than at high manifold pressure and low engine speed.

As there is considerable interest in high-altitude flight, it may be well to examine the chart to see how much the pitch must be reduced for the same speed at sea level. If an airplane is to be flown at 30,000 feet, it is found that the pitch must be reduced about 11° for sea-level operation assuming constant engine speed and power. Since the 11° reduction operation curve touches the envelope of efficiency curves at a speed corresponding to the latter part of the take-off run, there is no object in using a compromise propeller design. High-altitude designs are good sea-level take-off designs provided that the engine power is not reduced for take-off.

In conclusion:

1. Increased propulsive efficiency for take-off may be obtained at the expense of a small loss in high-speed efficiency by reducing the design pitch and increasing the diameter of controllable propellers.

2. The amount of improvement possible depends

roughly upon the high speed of the airplane—the greater the speed the larger the possible improvement.

3. This method may be applied to all types of engines, but less compromise is necessary to accomplish the same take-off efficiency for supercharged engines than for unsupercharged engines.

4. A change in air density from the critical altitude to the ground level and overspeeding the engine at take-off both effectively increase the take-off efficiency while boosting the engine at take-off decreases the propulsive efficiency.

5. Since overspeeding and boosting both increase the brake horsepower, overspeeding is preferable when the maximum power is limited.

## Discussion on "Propeller Advances"

### EDMUND T. ALLEN

Aeronautical advancement does not proceed on a smooth curve, onward and upward; it goes in jumps to plateaus where levelling off occurs and gains are consolidated. 1935 was such a period of levelling off after the initial perfection of the controllable propeller, retractable landing gears, flaps, and cantilever wing structures. From the operator's viewpoint this levelling off is significant. The Boeing Monomail of 1929 was the operator's first "modern" transport; but with a foot of snow on an airport at 6000 feet altitude above sea level, it would hardly get off,—in the absence of a controllable propeller. The development resulting from the demands of the Monomail brought the Boeing 247, the Lockheed Electra, and the Douglas DC-2, and likewise the Sikorsky S42, each demanding a little more of the designer in order to obtain high payload with high performance and ever increasing comfort,—all with relatively small horsepower per pound. We are prone to forget the great contribution which the controllable propeller has made to this picture. Without it no modern transport could operate.

The two-position type of controllable propeller is a compromise. Low-pitch cannot be set for maximum allowable power for take-off because with this pitch single engined operation near ceiling would be penalized. A compromise setting on the DC-2, for instance, permits 80% of rated brake horsepower for the initial part of the take-off run, 95% at the instant of leaving the ground, 105% during climbs at optimum climbing airspeed. For each of these conditions the engine-revolutions is necessarily different from the desired value. The high-pitch setting is likewise a compromise between the demands for obtaining cruising power at optimum cruising altitude without over-revving and for obtaining cruising power at low altitudes without over-supercharging. The constant speed propeller solves all these problems.

Modern transport flying has quite suddenly become enormously complex. The pilot's problems increase with each jump of aircraft development, no matter how automatic its new features. He now accurately controls his power-output amid the complexities of changing temperature and pressure, climbing, descending and cruising attitudes, and varying $V/ND$ ratios. Cruising power control is very accurately accomplished with the two-position propeller by the use of simple cruising charts which show the pilot at a glance the proper engine-revolutions to use for any desired power in any cruising altitude and temperature. For the constant-speed controllable propeller, engine-revolution lines are replaced on the charts by propeller-pitch lines or by manifold pressure lines. These are dependent variables and therefore any one of them is available as an indicator of the others. Climbing and descending operations are controlled in like manner by one or another of these variables.

For optimum economy of operation such control is essential. Savings of 15% in fuel alone have been achieved during the past year. The constant-speed propeller makes possible operation at best economy at low revolutions at high cruising manifold pressure. It is remarkably adaptable to optimum operation in all conditions.

### TH. TROLLER

*Daniel Guggenheim Airship Institute*

With increasing speed range of airplanes it becomes advisable to make use of high-lift devices on propeller blades as well as on airplane wings. When increasing pitch ranges are required, it is unavoidable that at least a part of the blade of standard airfoil section be stalling. By using high-lift devices it becomes possible to delay stalling considerably.

Some tests were made recently at the Daniel Guggenheim Airship Institute on propeller fans using boundary-layer suction to improve the fan characteristics. The test results are encouraging.

These tests were made with fairly thick sections. The thick sections would, in the light of test results by O. Schrenk, under certain circumstances also make possible a saving in weight, which becomes desirable when increasing propeller diameters become necessary with increasing power units.

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As the performance of airplanes has continued to increase, it has seemed that at some point further increases might be limited by the loss in take-off performance with high-pitch propellers. An analysis recently made by Mr. Biermann, of the N.A.C.A. staff, showed, however, that with controllable-pitch propellers this difficulty need not be feared, at least for some time to come. The efficiency over the range of speeds important for take-off, as for the flight range, is not far from a constant percentage of the ideal efficiency, and is therefore largely determined by the propeller diameter. To obtain a reasonably satisfactory propeller thrust for take-off, it is for this reason only necessary to provide a sufficiently large diameter and this can be done by gearing the propeller to have a suitable revolution speed.

The problem of strength of propellers is difficult and complex. Until recently the endurance limit of the materials has been known only for the condition in which the average stress was zero, a condition not found in propellers. Recently, L. B. Tuckermann, of the Bureau of Standards, has conducted tests on the fatigue strength of materials in which an oscillating load was superimposed upon a steady load. When sufficient information of this nature is available, it should be possible to make reasonably satisfactory computations of propeller stress except for the conditions in which there is resonance between the natural frequencies of the propeller blades or propeller-crankshaft combination in bending or torsion, and the load impulses. Some progress has been made in various places in the measurement of the natural frequencies of vibration of the propellers and crankshafts. Th. Theodorsen, of the N.A.C.A. staff, has developed a method of finding the natural frequencies that occur while the propellers are rotating, by means of tests on a slender model. Thus, some progress has been made in the problem of detecting and avoiding conditions of resonance, but the problem is an exceedingly complicated one and there is much yet to be done upon it.